Eos

SCIENCE NEWS BY AGU

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Tiny Volcanoes on Mars

Holy Water Miracles and a Climate Story

SCIENCE AT ITS CORE

WHETHER MADE OF ICE, SEDIMENT, OR PERMAFROST, DRILL SAMPLES ARE A TICKET TO OUR PLANET'S PROLOGUE.

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Cutting to the Core

We'll probably never get a real Jurassic Park—and that's almost certainly for the best—but we are learning quite a bit about what it was like to live during at least the final period of the dinosaurs.

In China's Songliao Basin, a research team on a drilling project called SK (initiated in 2006) has recovered 8,200 total meters of sediments spanning the entire Cretaceous. During one phase they drilled as deep as 7,018 meters. Their work will give us a thorough and fascinating look at terrestrial climate change during a time of rapid evolutionary turnover.

The heart of the SK team's research—and the theme of *Eos*'s July issue—is the study of cores. After completing the drilling phase last February, the team has now turned to inspecting their core samples. Read more on page 36, where Chengshan Wang and colleagues explain what they've discovered about "Earth's most intense greenhouse state of the past 150 million years" and what it could tell us about what humans might be in for as our climate continues to rapidly change.

Through sediment cores and ice cores, permafrost cores, and even tree rings, scientists have discovered myriad vehicles that allow us to look into the past. Collecting these time machines can be enormously expensive and time-consuming and sometimes only through rare, if terrible, opportunities—such as the chance to collect 9-meter-diameter "cookies" from giant sequoias after loggers felled a third of what is now Sequoia National Park in California, as Thomas Swetnam explains in our feature story on page 22.

Given the investment in collecting them, what do researchers do with all these cores once they've completed their initial studies? They put them in core libraries, of course, for the benefit of future research. And much like our traditional community libraries, core libraries need support and funding to make sure they survive. In the feature mentioned above, we look at how several collection caretakers are "future-proofing" these records, sometimes in dramatic scenarios, such as when Tyler Jones rushed to protect a freezer of ice cores at the Institute of Arctic and Alpine Research, or INSTAAR, in Boulder, Colo., in 2013.

Finally, even the best-protected library can be challenging to use if there is no indexing system. Nikita Kaushal and colleagues write on page 30 about their modern-day Dewey Decimal System for speleothems. Their clever standardization and categorization are already the basis of many papers by researchers who now have richer access to these paleoclimate cave specimens.

We finish off our look at core research with another delightful crossword puzzle from Russ Colson (see p. 48). We hope you can find time to take a break, center yourself, and dig right into our core clues.

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

Features

On the Cover

Air bubbles in an ice core from the Antarctic: The ice is up to 24,000 years old. Credit: Bernhard Bereiter/Scripps Institution of Oceanography/Empa/University of Berne

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Cold Curriculum for a Hot Topic

Middle school students from the Columbus City School District visit Ohio State University's campus during its Breakfast of Science Champions, where this group created its own ice core using everyday materials. Credit: Byrd Polar and Climate Research Center, Ohio State University

Whether it's dissecting a pig's heart or growing a bean plant in a paper cup, giving students hands-on experiences often helps them better absorb science lessons. That's why educators at the Byrd Polar and Climate Research Center do more than just talk about ice cores and what they reveal about temperature, precipitation, and climate: The scientists also help students create their own ice cores, using Pringles potato chip cans filled with layers of frozen water, instant coffee, and other materials to represent the different layers found in the ice.

"If you haven't seen an ice core and looked at what patterns are there, it's really hard to just jump to the data and have a deeper meaning of what [they're] telling you or how [they connect] to the core," said Jason Cervenec, education and outreach director at the Center, which is on the campus of Ohio State University (OSU) in Columbus.

Every year, Cervenec and his staff host thousands of kindergarten to 12th-grade students to teach them about ice cores and the secrets they hold. A handful of other facilities do similar educational outreach, including the National Science Foundation Ice Core Facility in Denver and the Climate Change Institute at the University of Maine in Orono.

Hands-On Learning

At the Byrd Center, a favorite activity for students is stepping into the −34°F freezer that holds ice cores extracted from glaciers around the globe. Paleontologists Lonnie Thompson and Ellen Mosley-Thompson, who collected many of the cores (now encased in silver canisters), often address the visiting school groups themselves, said Cervenec. The respected researchers are "as happy to do that as they are to talk to someone who is visiting from halfway across the world."

Cervenec and his staff also make interactive videos that teachers can download from the Center's website (bit.ly/Byrd-interactive-videos), offer virtual lessons to students anywhere in the world, and travel to local classrooms to share their ice core expertise.

Eric Sztul, a 7th-grade science teacher for the Columbus public schools, said his students love it when Cervenec brings crampons, parkas, and ice axes to show them what researchers wear to collect ice cores. "The kids always have lots of questions," Sztul said.

Climate Change Evidence

Cervenec said his group tries to make it easy for educators to teach about a variety of complex topics, including climate change. Ice core records allow scientists to reconstruct and compare past climates and their fluctuations, as well as show that Earth's current warming pattern is an anomaly.

A timeline graph at the Center, for example, connects proxy data found in an ice core with world events so students can see how warming fluctuations have become much more severe since the Industrial Revolution.

"I love learning about climate change throughout geologic time and then looking at that in reference to real time," said Claire Monk, who teaches environmental science and geography at New Albany High School, 32 kilometers northeast of OSU.

Monk regularly takes her students to the Center and also has them create ice cores in the classroom. They add a layer of cinnamon to represent deposited volcanic ash, for example, and a layer of seltzer water to illustrate carbon dioxide bubbles trapped in ice.

One of Monk's former students, Chloe Platte, said the knowledge she gained came in handy. "I convinced my dad that climate change was real," said Platte, now a sophomore at Clemson University. "He was skeptical, like, 'We don't have the data for X many years ago.' And I was like, 'Yeah, we do in ice cores.'"

When high school and college students come to the Center, they can also engage in lessons analyzing radioactivity data extracted from ice cores from the Greenland Ice Sheet. The data come from dust that wind carried to glaciers in the 1950s and 1960s when the Soviet and U.S. governments were performing aboveground testing of nuclear bombs. "What [students] do essentially is use that as a reference point to put an age to the ice," said Stacy Porter, a postdoctoral paleoclimatologist at the Center who teaches that lesson. "Because one of the key points of doing ice core research is that if you don't have a proper timescale, your data are kind of useless."

The Byrd Center's lessons seem to be working; both Sztul and Monk said they have former students who've become inspired to study environmental topics in college.

"There's no question it inspired me," said Zoe Kellerman, one of Monk's former students who is studying environmental science and sustainability at Rollins College in Florida. "Learning about the ice cores was such an eye-opening experience."

By **Nancy Averett** (@nancyaverett), Science Writer

The Chaos Beneath a Glacier's Calving Front

While enjoying a fondue dinner next to Bowdoin Glacier, researcher Evgeny Podolskiy watched as a nearby ice-dammed lake slowly drained.

Bowdoin Glacier is one of approximately 250 marine-terminating glaciers in Greenland, and what Podolskiy witnessed was the result of a subglacial discharge plume, a unique feature of marine-terminating glaciers. The glacier's melting surface water falls through its crevasses and cracks into channels and exits underneath, at the glacier's edge, where it mixes with salty fjord water. When the freshwater from the glaciers combines with the salty water, it creates a convective plume, like a chimney, and can form pools. If the plume's deep water is warmer than its shallower water, it can quickly melt the ice above, which can cause a piece of the glacier to break off into the ocean.

These Arctic subglacial plumes "are key drivers of fjord-scale circulation," said Podolskiy, an assistant professor at the Arctic Research Center of Hokkaido University, yet much about their long-term activity, how they change, and how they affect the underwater environment has been a mystery.

Podolskiy and his colleagues wanted to know what was really happening in subglacial plumes and their effects on their environments, but glaciers are dangerous and unstable places, making them difficult for scientists to study. Marine-terminating glaciers, in particular, move very quickly—for example, Bowdoin moves 1–3 meters every day. It also has many crevasses into which researchers could fall. However, Bowdoin Glacier is unique because one area of its calving front can be reached by foot. "So we can do things which not many glaciologists could imagine," said Podolskiy.

Previously, data on subglacial plumes had been limited to very brief, episodic periods, and a full picture of plumes had not been achieved. In an effort to get a "continuously updated image" and not just "snapshots" of subglacial plumes, the researchers devised an innovative method to gather longer-term data that involved hanging two sensors from a 30-meter ice cliff. One sensor was hung at 5 meters below the glacier's calving front, and the second, a deepwater sensor, was hung at 100 meters in the water of an ice-dammed lake. The sensors were left there for 18 days. The researchers also set up a camera to capture time-lapse images of the lake every minute. This was the first continuous sensor monitoring done at a calving front, and the results were published in *Communications Earth & Environment* (bit.ly/sensor-monitor).

Three researchers run cables attached to sensors at Bowdoin Glacier's calving front. Credit: Evgeny A. Podolskiy

The sensors were regularly spit out to the surface by the plumes and periodically dragged by nearby icebergs that caught the sensors' cables in passing.

Feasts for Birds

What the authors discovered was chaos and disruption beyond what they had imagined. The sensors recorded extremely irregular and dramatic activity—bursts of warm water from beneath the glacier formed pools near the calving front, which would be sucked back under hours later by the plume, triggering a seismic tremor lasting several hours. In addition, tides, tremors, and wind all affected the plumes' activities, the authors discovered. The sensors were regularly spit out to the surface by the plumes and periodically dragged by nearby icebergs that caught the sensors' cables in passing. These challenges are why the researchers have only 12 days of data, rather than 18 as planned. "This kind of time-lapse profiling of the water column is extremely unusual, to my knowledge, especially near the surface, because near the surface, your sensors are just destroyed by these icebergs," said Podolskiy.

These plumes also push nutrients, sediments, and organisms—including zooplankton on which birds feast—to the surface. Near the coast, Podolskiy occasionally found deepwater fish with their eyeballs burst because of barotrauma, damage caused by an abrupt change in pressure. These fish provided food

An image taken from a helicopter shows the deep-water sensor cable at the calving front being dragged away from the ice cliff by a strong under-water current created by a subglacial plume. Credit: Shin Sugiyama

for birds and foraging seals. "One of the most amazing things I saw in this Arctic desert [was] the formation of foraging hot spots," he said. "You may see above this brownish water hundreds of birds and seals attracted to it, because it brings things up from the deep ocean."

Ken Mankoff, a scientist at the Geological Survey of Denmark and Greenland who works in similar environments but wasn't involved in the study, called the approach "innovative and elegant." He added, "The time series is critical, because if you just have the snapshots, you don't know clearly what's going on there."

Only in the past decade have researchers begun to realize how much glaciers affect the ocean, Podolskiy said, yet predictive models that are currently used are based on very brief timescale data captured in deeper, calmer waters. He hopes this research will prompt more longer-term observations of subglacial discharge plumes. "How do you assess the future of glaciers when we are not even sure what the systems are doing, really?" he asked.

By **Danielle Beurteaux** (@daniellebeurt), Science Writer

Cheap Sensors Provide Missing Air Quality Data in African Cities

Particle pollution poses hazards to human health, and among the most dangerous of air pollutants are concentrations of particle pollution smaller than 2.5 micrometers, also known as $PM_{2.5}$. These fine particles can settle deep in the lungs and enter the bloodstream. Researchers have also connected $PM_{2.5}$ to respiratory ailments and premature death. Yet many locales lack information about ambient air quality. This dearth of data stems partly from the initial and continued expense of air quality monitoring equipment.

Now researchers have used low-cost sensors to collect years of data on particle pollution at sites in two cities in sub-Saharan Africa: Kinshasa and Brazzaville. In Kinshasa, Democratic Republic of the Congo, and Brazzaville, Republic of the Congo, $PM_{2.5}$ levels are more than 4 times the standard set by the World Health Organization, researchers reported on 25 March in *Aerosol and Air Quality Research* (bit.ly/air-pollution-africa). The new data highlight a need to improve air quality in these cities.

To date, there's very little information on air pollution in these two cities, said Paulson Kasereka, a natural resources specialist at Ecole Régionale Postuniversitaire d'Aménagement et de Gestion intégrés des Forêts et Territoires tropicaux (ERAIFT), a postgraduate school in Kinshasa that focuses on tropical forest management. "We are not aware of how many lives may be [lost] from this," said Kasereka, one of the study authors. "We are not aware of how many people are suffering from diseases that are caused by air pollution." With human health on the line, low-cost sensors could be an attainable answer to increased air pollution monitoring, and Kasereka hopes that data from this study could spur government action to curb air pollution and, in conjunction, reduce air pollution-related health risks.

> **"We are not aware of how many people are suffering from diseases that are caused by air pollution."**

Two capital cities lie on opposite banks of the Congo River. Brazzaville (the capital and largest city of the Republic of the Congo) is on the northern side of the river, and Kinshasa (the capital and largest city of the Democratic Republic of the Congo) is on the southern side. Credit: NASA's Marshall Space Flight Center, CC BY-NC 2.0 (bit.ly/ccbync2-0)

More Accessible Monitoring

The study involved deploying low-cost PurpleAir $PM_{2.5}$ monitoring sensors. These monitors collect air quality data in real time and cost about $250 each. Four sensors were used in Kinshasa, where 14.3 million people live, and one monitor was placed in Brazzaville, which has a population of 2.4 million. At one site in Kinshasa, a sensor collected data between March 2018 and July 2020, and at the other sites, data collection occurred between November 2019 and September 2020.

The low-cost sensors used by the team cost about 100 times less than research-grade reference monitors, the authors wrote. However, low-cost sensors are cheaper for a reason, said atmospheric scientist Dan Westervelt of Columbia University's Lamont-Doherty Earth Observatory in New York, who is also part of the research team. For example, the optics and instrumentation used to measure particles are more rudimentary than research-grade reference monitors.

For more accurate data, the researchers needed to calibrate their low-cost sensors. To do this, they placed a low-cost sensor beside a more sophisticated, expensive instrument located in Kampala, Uganda—which is located about 2,000 kilometers (about 1,240 miles) from Kinshasa—to watch how data from the devices differed. Using 6 months of the side-

by-side particle pollution data, combined with humidity and temperature measurements as inputs, the team built a model to correct data collected from the low-cost sensor.

Although Kampala is located far from Kinshasa, these cities have similar temperature and humidity levels, Westervelt said. "We were able to get a really decent model. This is one of the first efforts to calibrate a low-cost sensor in sub-Saharan Africa."

The calibrated data revealed trends in $PM_{2.5}$ pollution in Kinshasa and Brazzaville. Particle pollution tended to be highest in the early mornings and around dinnertime, which may relate to activities such as commuting, cooking, and burning trash, which is one of the main means of disposing of waste, Westervelt said. The scientists also observed a roughly 40% drop in PM2.5 due to COVID-19 lockdowns in Kinshasa during April 2020. However, the authors noted that future studies should use more sensors to understand local conditions throughout cities.

In Kinshasa (pictured here) and Brazzaville, $PM_{2.5}$ levels are more than 4 times the standard set by the World Health Organization, according to new research. Credit: MONUSCO Photos, CC BY-NC 2.0 (bit.ly/ccbync2-0)

Future Efforts to Improve Air Quality Monitoring

Even with the limitations of low-cost sensors, the team's approach could enable more widespread air quality monitoring. Many low-cost sensors could gather data and be calibrated against one monitor in a nearby city or region, said Deo Okure, an air quality scientist at AirQo in Kampala, who was not part of the work.

The team plans to add sensors in other cities in the Congo region and sub-Saharan Africa. Another next step could be to investigate the sources of air pollution, Okure said. Particle pollution in this region comes mostly from transportation, energy, and industry. For instance, vehicles emit particle pollution and kick up dust on unpaved roads. Particle pollution also comes from the wood or coal burned to heat homes and cook. Data that detangle these contributions could inform efforts to improve air quality.

These sorts of calibrated low-cost sensors could boost air quality monitoring programs in a sustainable way, Okure said. For instance, communities could host the sensors, and schools or clubs could analyze the data. Community involvement, he said, would go a long way toward raising awareness around air quality issues.

By **Carolyn Wilke** (@CarolynMWilke), Science Writer

Laser Flashes Shed Light on a Changing Arctic

Earlier this year, several researchers traded the relative warmth of Albuquerque, N.M., for the bone-chilling winter conditions of far northern Alaska. They made the journey to monitor pulses of laser light zipping through a strand of fiber-optic cable buried beneath the Beaufort Sea. These observations, part of a 3-year project, will shed light on the prevalence of anthropogenic activity in the region and how it's responding to a warming climate.

The Burden up North

Far northern latitudes bear an unusually heavy burden when it comes to climate change: Temperatures are warming there faster than they are elsewhere. Permafrost in the Arctic that's been frozen for thousands of years is thawing, rendering topsoil unstable and priming the environment for erosion and the accompanying release of greenhouse gases. "It's a very critical region," said Michael Baker, a seismologist at Sandia National Laboratories in Albuquerque.

In February, Baker and several colleagues traveled to the northern coast of Alaska to study the Arctic. But rather than bring with them sensors that would need to be deployed, regularly monitored, and finally retrieved, they relied on something far more suited to the fragile, changing environment: a fiber-optic cable already buried meters beneath the seafloor. Installed in 2017, the cable is part of a telecommunications network that will eventually span from London to Tokyo. It contains 16 glass fiber-optic strands, and one of those, not currently used, is being repurposed for science.

Flaws Reveal Vibrations

Fiber-optic strands are typically used to transmit light, which encodes data. But these strands, each about as thick as a human hair, can also function as sensitive detectors of environmental change, said Rob Abbott, a geophysicist at Sandia National Laboratories who is leading the investigation. By sending pulses of laser light into a fiber-optic strand and then measuring how a tiny bit of that light is reflected back by intrinsic flaws in the strand, it's possible to trace how different parts of it are vibrating, he said. "Those vibrations can be caused by any number of environmental, anthropogenic, or biogenic sources."

This technique, known as distributed acoustic sensing, is gaining traction in the field of seismology. It's also useful for monitoring active volcanoes, detecting changes in traffic patterns during the pandemic, and even picking up ground shaking caused by a parade's floats and marching bands.

Distributed acoustic sensing is perfect for monitoring landscapes that are difficult to access or that benefit from minimal human interference, said Eileen Martin, a data scientist at Virginia Polytechnic Institute and State University in Blacksburg not involved in the research. The infrastructure needs to be installed only once, and data can be collected effectively continuously, she said. That's "a huge win for distributed acoustic sensing technology."

Researchers are using a single fiber-optic strand to trace how the Arctic is changing. Credit: Kyle R. Jones

Don't Forget Anything

In early February, Abbott, Baker, and another geophysicist traveled from Albuquerque to Oliktok Point, Alaska. The journey involved four airports and a 3-hour drive on an ice road. Oliktok Point is pretty remote, said Abbott. "If you forget something back in Albuquerque, there's really not much you can do about it." The winter conditions were tough too, said Baker. "We saw −44°F with −70°F wind chill one day."

The team monitored a 39-kilometer stretch of fiber-optic cable buried beneath the floor of the Beaufort Sea. Over 7 days, they collected observations from roughly 20,000 distinct sections of the cable. "We take data every 2 meters," said Abbott.

The researchers have already spotted a variety of events, some environmental and some anthropogenic, in the rich data set. They've detected the signatures of ice quakes, a hovercraft, and ocean waves, among other processes. The scientists plan to return to Oliktok Point seven more times over the next 2 years to collect more data. This longitudinal view, over multiple seasons, will allow them to trace how the Arctic is changing, said Abbott. It will be possible to monitor the thickness and breakup of sea ice and the intensity of Arctic storms, the researchers suggest. Whale song might also show up in the data sets, said Abbott, which would allow the team to trace the animals' migration patterns. "It'll be in the right frequency range."

There's an enormous amount to learn about how the Arctic is changing, said Abbott, but doing that will require sifting through troves of data. The February trip alone yielded about 20 terabytes, he said, so data storage is something to think about. "We're probably going to buy a half-petabyte worth of disk drives."

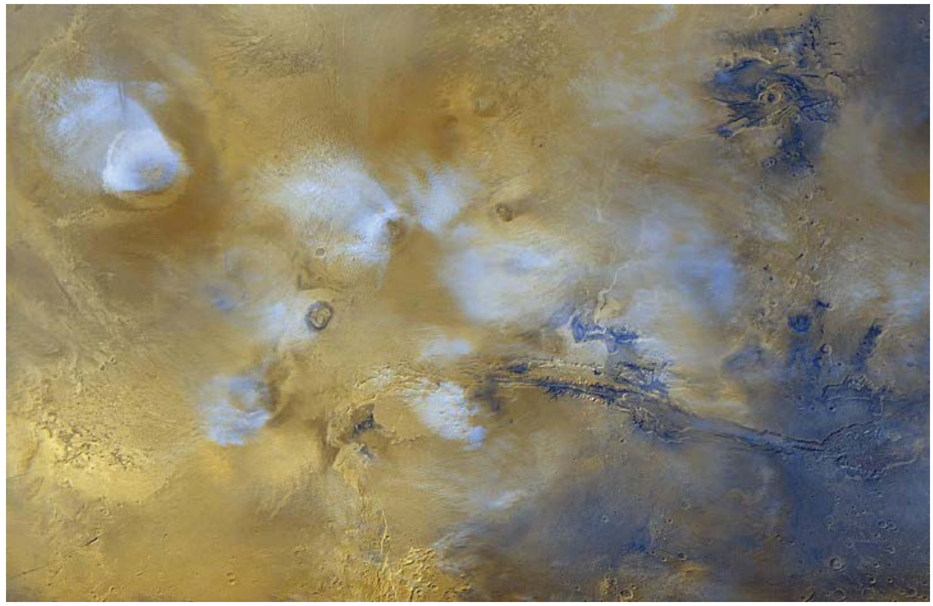
By **Katherine Kornei** (@KatherineKornei), Science Writer

Tiny Volcanoes Are a Big Deal on Mars

Life might be the focus of Mars exploration today, but what we already know for sure is that our planetary neighbor is home to the largest volcanoes in the solar system. Olympus Mons towers 23 kilometers (75,000 feet) over the surrounding landscape, and its neighbors, the Tharsis Montes (Arsia Mons, Pavonis Mons, and Ascraeus Mons), stand out as a line of volcanic giants. These are the most prominent volcanic features on the planet, but a new study suggests that thousands of small volcanoes litter the landscape.

Small volcanoes are surprisingly important for understanding the volcanic history of a planet. On Earth, cinder cones and fissure vents are found all over volcanic terranes and, in many locations, may volumetrically be as important as larger shield volcanoes or stratovolcanoes. The contribution of these smaller volcanic features piqued the interest of Jacob Richardson, an assistant research scientist at NASA's Goddard Space Flight Center in Greenbelt, Md., and lead author of the new study.

"We know a lot about the big volcanoes of the Tharsis Province, but what about all the smaller vents?" said Richardson when asked about what spurred the study, published in the *Journal of Geophysical Research: Planets* (bit.ly/tharsis-province-volcano). "What is the extent of all these small volcanoes, and what is the nature of their relationship with all the big volcanoes?"



The Tharsis Volcanic Province on Mars includes big volcanoes like Olympus Mons (top left) and the Tharsis Montes (Ascraeus Mons, Pavonis Mons, and Arsia Mons, center diagonal from top to bottom). New research indicates that smaller volcanoes in the region, too, provide key clues to the evolution of the Martian crust and mantle. Credit: NASA

Tracking Down Volcanic Vents

Richardson and his colleagues identified more than 1,000 small volcanic vents in the Tharsis Volcanic Province, an area roughly the size of Africa. Most vents were less than 100 meters tall, which isn't much different than the heights of such vents on Earth. Many of these ancient vents might be analogous to the fissures and small cones formed during the 2020–2021 basaltic eruptions on the Reykjanes Peninsula in Iceland.

Richardson and his colleagues used high-resolution camera imagery as well as infrared and laser altimetry data from a variety of Mars orbiters to compile a database of these small volcanic features. The ages of the features range from 3 billion years to less than 250 million years, some likely only tens of millions years old, and imply that a new volcanic vent formed somewhere in the province every 3 million years.

Although the resolution of the data sets allowed for identification of these features, trying to decide what constituted a "volcanic vent" was challenging, according to Richardson. Many times, erosion and faulting destroyed potential vents over the millions to billions of years since they formed. On top of that, Martian dust and sand have buried many vents. Even identifying fissure vents (which can stretch long distances with low elevation) versus cones (which are more compact but have higher elevation) is difficult. This challenge makes the catalog only a minimum estimate of potential small volcanic vents across the Tharsis Volcanic Province.

Although the resolution of the data sets allowed for identification of these features, trying to decide what constituted a "volcanic vent" was challenging.

Independent Venting

The researchers' census shows the importance of small volcanoes in the Tharsis Volcanic Province, where previously only the Tharsis Montes and Olympus Mons were appreciated. The existence of these small volcanoes suggests spatially broad and long-lived magmatism in the region. When taken as a whole, these clusters of hundreds of vents may have contributed the same volume of lava as the big Tharsis Montes volcanoes, albeit over longer periods of time.

These small vents likely aren't directly tied to the larger volcanoes. On Earth, large shield volcanoes that are waning in activity, such as Hawaii's Mauna Kea, have small vents littering their slopes. On Mars, however, the abundant small volcanic vents are not on the flanks of the Tharsis Montes and Olympus Mons. Instead, they are to the east of the line of volcanoes, suggesting that they might have had their own magmatic source that fed eruptions over the past 500 million years.

The new study "adds information about the long-term evolution of the crust and mantle on a planet that lacks tectonics."

Why this difference in volcanism? Richardson and others think that magma under the Tharsis Montes might more efficiently reach the surface by following preexisting fractures in the crust. However, the crust to the east doesn't appear to be as fractured, so the magma can't follow these same efficient routes. Instead of a big volcano like Arsia Mons forming, you get smaller, distributed volcanoes.

Better Understanding the Martian Mantle

Mariek Schmidt, an associate professor of Earth sciences at Brock University in Ontario who was not involved in this study, said the new study supports our understanding of the Martian mantle. "The strong tectonic control on vent distributions, rather than focusing at large shield volcanoes, is consistent with our understanding of Mars's prolonged igneous history involving thickening of the lithosphere and lower inputs of mantle melting over time."

Lionel Wilson, an emeritus professor at Lancaster University in the United Kingdom who was also not involved in this study, called the new research an extremely valuable systematic catalog of volcanic activity in the Tharsis Volcanic Province. These big data sets allow for analyses that weren't possible before, he said.

"It helps us think about the contribution of volcanic gases to the atmosphere over geologic time," said Wilson. "More generally, it adds information about the long-term evolution of the crust and mantle on a planet that lacks tectonics." That gives us an end-member to understand our own planet. "Mars is by far the best candidate for trying to understand why Earth was the only one of Venus, Mars, and Earth that developed plate tectonics. The data in this study are a major contribution to this question."

By **Erik Klemetti** (@eruptionsblog), Science Writer

Narwhal Tusks Record Changes in the Marine Arctic

A narwhal's iconic spiral tusk can be used to trace the animal's environment and food supply throughout its life. Credit: ©Paul Nicklen/paulnicklen.com

As the Arctic continues to warm, climate changes cascade into the marine environment. Top predators like polar bears, beluga whales, and narwhals are affected by shifting seasonality and loss of the Arctic sea ice that shapes where they live and what they eat. Moreover, changes in ocean currents alter the transport of toxins like mercury through Arctic waters, which can create health concerns for top consumers in marine food webs.

Historically, it has been difficult to track how decades of changes in the marine environment have affected the denizens of the Arctic deep. A recent *Current Biology* study has shown, however, that the iconic spiral tusks of male narwhals record chemical tracers of diet and mercury exposure over the animals' lifetimes and provide a new paleorecord of the Arctic (bit.ly/narwhal-tusks).

"The tusk is a relatively rare sample to get ahold of…but what's unique about them is that we can do a time trend analysis for each individual," which hasn't been possible before, said Jean-Pierre Desforges, a postdoctoral fellow in marine mammal toxicology at McGill University in Montreal who coauthored the new study. "We don't have that many tusks, but for each tusk we have a lot of data points."

A Change in Diet

Narwhals spend months at a time under Arctic sea ice in remote areas of the world, which can make sample collection very challenging. To date, most data on the impacts of climate change on narwhals come from tissue sampling, which can provide a brief snapshot of an animal's environment. If researchers wanted to understand these impacts over a narwhal's 50-year life, they'd have to collect tissue samples for 50 years. This limits analysis of a trends across a narwhal's lifetime—the samples might come from many animals, or different collection methods might be used. In population-level studies, trends can be overwhelmed by variations among individual animals.

Narwhal tusks provide an alternative. A tusk is an enlarged canine tooth that grows a little bit each year and is connected to the animal's circulatory system. Like whale earplugs, baleen, hair, and teeth, narwhal tusks can be a valuable archive of the animal's environment and habits. A single tusk provides decades' worth of data for a single narwhal. "From the time the animal was killed, we can backtrack through the animal's whole lifetime," Desforges said.

Desforges and his colleagues collected 10 narwhal tusks, each about 1–2.5 meters in

length, from animals that lived in the waters off northern Greenland. The team measured stable isotopes of carbon and nitrogen—δ^{13}C and δ^{15}N—as well as mercury levels at multiple points along the length of each tusk, representing growth from 1962 to 2010.

"The carbon isotopes are pretty good trackers of habitat use," Desforges said. "The signals of carbon are very different if you're feeding nearshore or offshore, like deep in the ocean; if you're feeding along the sediment at the bottom of the ocean or within the water column…; and if you're feeding along the ice-associated food web." Nitrogen isotopes track where on a food web an animal is eating. By combining information from the two isotope signals the team was able to decipher broad trends in the narwhals' diets over their lifetimes.

The tusks revealed that before 1990, the narwhals' diet primarily came from sympagic food webs associated with sea ice and with fish like halibut and Arctic cod. After 1990, narwhals primarily ate open-water (pelagic) food like capelin and armhook squid. This pattern broadly matches observed changes in Arctic sea ice and marine habitats during the study period: Climate-driven changes in the ocean have pushed more pelagic fish into icy Arctic waters, and with less sea ice, narwhals have had to shift where they hunt to better avoid predators like orcas.

Carbon and nitrogen stable isotopes in the layers ofa male narwhal's tusk track whether the animal's food source is from sea ice–dominated waters or open ocean. Credit: Rune Dietz

Mercury Marks Human Impact

As with δ^{15}N, mercury levels track food web position. In the tusk samples, mercury levels rose with an animal's age and declined as its food source shifted from sympagic prey, which are often at higher trophic levels and have greater bioaccumulation and biomagnification of toxins, to pelagic prey. Temporal trends in the tusks' mercury and nitrogen matched until 2000, when they sharply diverged.

"The diet suggests that mercury should be going down, whereas the mercury levels rise," Desforges said. "Not only that, they rise a lot faster than they had in the previous decades. So the diet is not the major driver of mercury in recent decades. We propose that [the increase in mercury is associated with] increased global emissions of mercury or else a climate change impact where mercury is becoming more available in the Arctic."

Analyzing more tusks collected in Greenland and elsewhere could help scientists trace where the mercury is coming from and better understand the potential health impacts of mercury on Arctic marine mammals.

Narwhal tusk expert Martin Nweeia, a dental researcher at Case Western Reserve University in Cleveland, Ohio, and Harvard University in Cambridge, Mass., told *Nunatsiaq News* that insights from tusk samples should be seen as one piece of the puzzle in tracking environmental change (bit.ly/Nunatsiaq-news). Nweeia, who was not involved with this study, agrees with the researchers that tissue samples and actual stomach contents of tusked and nontusked males and females are needed to see the whole picture. He added that the best way forward would be to work with Inuit and let traditional knowledge guide that work. "I'd be curious what hunters think, because they're cutting open stomachs all the time," he said. "They know exactly what that diet is."

The tusks used in this study were provided by Avanersuaq and Uummannaq hunters after traditional subsistence hunts, but "we probably have tusks in museums around the world dating back to who knows when," Desforges noted. "We can get really valuable information if the tusks are in good shape and preserved in the right way. Samples go back in time before the Industrial Revolution, so we could get a good idea of what the prehuman baseline would be for mercury in marine mammals."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Holy Water: Miracle Accounts and Proxy Data Tell a Climate Story

St. Fridianus is credited with diverting the course of the Serchio, a Tuscan river, in the 6th century—a period during which the North Atlantic Oscillation was particularly intense. Credit: Filippo Lippi/Uffizi Gallery, public domain

In early medieval Italy (then a troubled peninsula transitioning from the collapse of Roman rule) a group of monks at a mountaintop monastery had a water problem. To fetch their supply, they needed to descend from the monastery's steep and rocky perch. To their aid came St. Benedict, who spontaneously brought water to the summit in the form of a spring.

According to a new study, this account does more than relate the performance of a miracle (bit.ly/climate-change-medieval-Italy). It also suggests that climate change played a previously unassociated role in societal shifts long recognized by historians.

The study, published in the journal *Climatic Change,* brought together an international group of geoscientists and historians led by researchers at the University of Warsaw and the University of Pisa. Authors examined both paleoclimatological proxy data and historical records to gain a fuller picture of the impact that a prolonged period of increased rainfall had on Italian society in the 6th century. Their findings indicate that contemporaneous water-related miracle stories go beyond the anecdotal to reveal one way local Christian leaders responded to a period of climate extremes.

A Stormy Century

After the collapse of the Western Roman Empire in the late 5th century, central and northern Italy came under siege by invading forces, and decades of war left the peninsula hobbled and depopulated. Into this maelstrom swept a century-long spell of bad weather, a circumstance that provided rich material for Pope Gregory I (Gregory the Great), whose *Dialogues on the Miracles of the Italian Fathers,* written in the 590s, included descriptions of holy figures bringing forth storms, conjuring new water sources, and rerouting troublesome rivers.

Hagiographical accounts are generally considered anecdotal or derivative. But when combined with proxy data, the *Dialogues'* water-related stories, along with those of other 6th century writings, may demonstrate that the society affected by the century's changing weather patterns also responded to attempts to explain or contextualize them.

"Even when climate is not causing the economic or social system to collapse, there might be some important influences, some impact on other levels of human functioning…on our thinking and our behavior," said study coauthor Adam Izdebski, an independent research group leader at the Max Planck Institute for the Science of Human History. It can be as simple, he said, as people noticing the weather and leaders taking advantage of that awareness. For Gregory, it was an opportunity to move the cultural tide in the church's favor.

"Hagiographical sources show us the world as the people who produced them saw it," said Samantha Kahn Herrick, an associate professor of history at Syracuse University who was not involved in the study. "They reveal how people made sense of what was happening. Even historical sources that seem much more banal and straightforward are always shaped by their authors' sense of what's possible and what's important."

A Layered Story

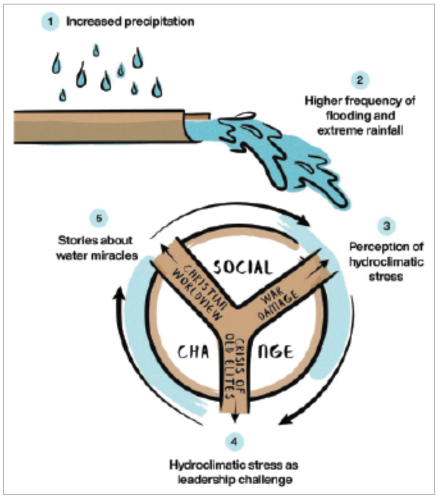
Researchers obtained climate data by analyzing a stalagmite collected from Renella cave, located near the town of Lucca in northern Tuscany. By measuring oxygen isotope ratios in the stalagmite's layers, researchers were able to determine whether environmental conditions were wet or dry when the layers were formed. They then used uranium-thorium dating to pinpoint when those conditions occurred. The stalagmite provided nearly a thousand years of data from the period before 900 CE and showed that northern and central Italy experienced hydrological extremes during the 6th century.

The culprit, according to study authors, was likely a negative phase of the North Atlantic Oscillation (NAO), a winter weather pattern that brings moisture from the Atlantic Ocean to parts of Mediterranean Europe, in this case resulting in decades of increased precipitation during the colder months. Researchers analyzing the stalagmite from Renella found that in the 6th century, precipitation in the region was distinguished by a particular isotopic trace that's left by moisture from the Atlantic.

The Saints Go Marching In

In Lucca, local legend credits St. Fridianus, a 6th century bishop, with redirecting the flood-prone Serchio River away from town, a story that appeared in—and may have originated with—the *Dialogues.* By directly addressing a preoccupation of the times, accounts of miracles like those performed by Benedict and Fridianus would have served to strengthen the cult of saints, then a relatively new phenomenon, and concentrate power in the hands of local bishops, keepers of sacred relics that could bring protection against demons, illness, fire—and floods.

To analyze whether such stories went beyond the application of familiar literary



This diagram shows the network of relationships between increased precipitation and social change in 6th century Italy. Credit: Drawing by Michelle O'Reilly, MPI SHH; design by Adam Izdebski, https://doi.org/10.1007/s10584-021-03043-x, CC BY 4.0 (bit.ly/ccby4-0)

motifs, researchers mined works contained in the Cult of Saints in Late Antiquity database, a collection of texts spanning around 5 centuries that an Oxford-based team has been working to catalog since 2014. Study authors found that hagiographies from the eras immediately preceding and following the study period had nearly no mention of water miracles, nor did such stories appear significantly in the contemporaneous works of the Frankish historian and bishop Gregory of Tours, who chronicled events outside the area that would have been affected by the negative NAO. In addition, only some of the water miracles related in the *Dialogues* echo earlier works in the genre. Others scenarios are, as researchers wrote, "either new or strangely overrepresented."

Contemporaneous nonhagiographical works written about northern and central Italy in the 6th century—such as the letters of Roman official Cassiodorus and Paul the Deacon's *History of the Lombards*—also reveal evidence of increased precipitation through passing remarks about flooding and torrential rain. "They confirm the impression we have from Gregory's *Dialogues*," said Robert Wiśniewski, a study coauthor and historian from the University of Warsaw.

According to Wiśniewski, Gregory's body of work indicates that he was unlikely to tell stories that wouldn't influence his audience. Therefore, his uncommon inclusion of a relatively large number of water miracles in his *Dialogues*—they make up 20% of the text—suggests that he was aware of how the changing climate had affected the population and that he used the stories as tools to demonstrate the ability of the church, and saints in particular, to offer solutions.

Better Together

The study's interdisciplinary approach was key to making connections that, according to Izdebski, "are very unusual and far from obvious." Working separately, neither the team of geoscientists at Renella cave nor the study's historians might have been able to access or interpret the data needed to draw their conclusions.

"The way they put all of these different data into conversation was valuable both in terms of their conclusions and in terms of showing that historical evidence could influence interpretation of the scientific data," said Herrick. And the impact goes both ways. "Perceptions of reactions to climate change are going to be fundamentally shaped by the culture, as well as the political and economic and social structures of a society, which I think is an important thing for scientists to recognize."

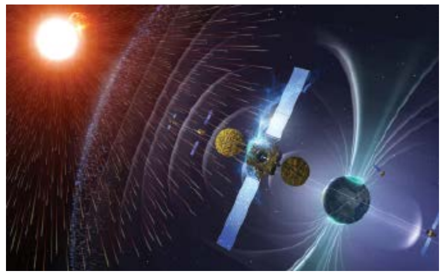
By **Korena Di Roma Howley** (korenahowley@gmail.com), Science Writer

Taking Stock of Cosmic Rays in the Solar System

Scientists hope to find traces of life in exoplanet atmospheres by looking for telltale patterns in an atmosphere's chemical composition. Those patterns, however, could be altered by cosmic rays. As these energetic charged particles smash into planetary atmospheres at reasonable fractions of the speed of light, they create cascades of secondary particles and radiation that alter atmospheric chemistry. At the extreme, the invisible particles shape a planet's capacity to host life.

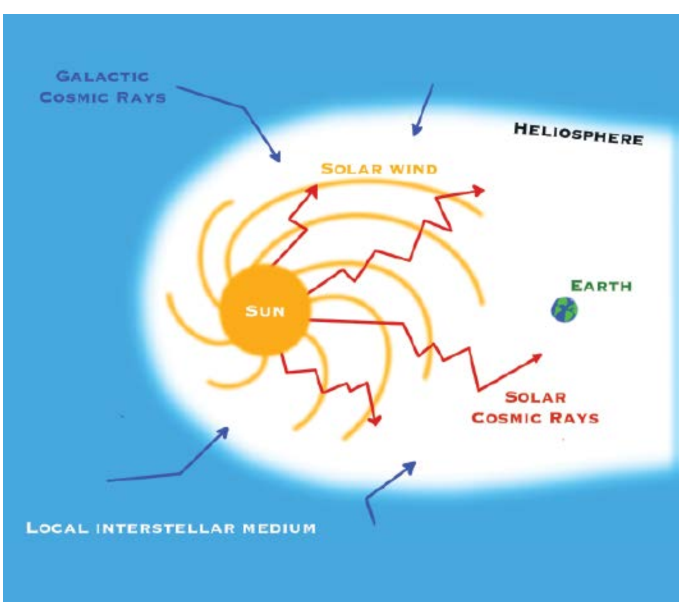
Cosmic rays' behavior and impact are poorly understood even in our own solar system, let alone around another star. A team of researchers recently investigated the history of cosmic rays' barrage on Earth. In a recent paper published in *Monthly Notices of the Royal Astronomical Society*, the team showed how the production and transport of cosmic rays in the solar system have changed throughout the Sun's lifetime (bit.ly/cosmic-rays-change). The insight may help facilitate the search for life using atmospheric signals.

Planets encounter cosmic rays mostly from two distinct sources. One source is the planet's star, which produces stellar cosmic rays: Stars spew out high-energy particles, primarily protons and the nuclei of helium atoms, through the flares and coronal mass ejections that also feed stellar winds. (Although they come from the same source, a stellar cosmic ray has a million times the energy of a stellar wind particle and is much rarer.) A second, more constant source of cosmic rays is the Milky Way itself, which produces galactic cosmic rays: These particles arise from the remnants of supernova explosions and swarm all over the galaxy.



High-energy particles, also known as cosmic rays, permeate the solar system. Credit: ESA

"The shape and irregularities of the solar magnetic field determine how particles travel in the solar system," said Donna Rodgers-Lee, lead author of the study and a postdoctoral researcher at the University of Dublin. Solar particles are shoved, pushed, and thrown around by magnetic fields as they move away from the Sun. Galactic particles, on the other hand, need to overcome the push of the solar wind as they move in proximity to the Sun. An increase in stellar cosmic rays usually sweeps away incoming galactic cosmic rays, which are then observed to decrease during that time.



This diagram of the solar system shows the solar wind, solar and galactic cosmic rays, and the heliosphere. The magnetized solar wind determines cosmic rays' paths. Credit: Sarah. A. Brands

Modeling a Young Sun

The younger Sun was more magnetically active and interacted differently with both types of cosmic rays. It used to produce more particles, and its solar wind extended farther into space, which changed the relative contribution of solar and galactic cosmic rays on planets in the solar system. "The fluxes at the position of Earth are anticorrelated. Stellar cosmic rays' flux was larger when the Sun was younger, and galactic cosmic rays' flux was lower," said Rodgers-Lee.

Federico Fraschetti, a visiting scientist at the Harvard-Smithsonian Center for Astrophysics and senior scientist at the University of Arizona, welcomes studies like this one. "Knowing the absolute flux of energetic particles from the Sun at a given energy and how it relates with the total energy released in coronal flares will be very valuable," he said. Fraschetti was not involved in the research.

However, Fraschetti pointed out, the team used a simplified model to calculate the transport of particles through the solar magnetic field. A more comprehensive model that includes the solar wind's natural eddies and turbulence might lead to additional surprises, especially for the very energetic particles.

Cosmic Weather Around Other Stars

Although the solar system is the principal arena for studying cosmic rays, findings aren't directly applicable to other stars. Production of cosmic rays varies from star to star, as does stellar rotation and the consequent patterns of stellar magnetic fields. The present study addressed those variables by simulating the Sun's evolution, but the options for study are far from exhausted.

Rodgers-Lee and her team will use their findings to study a sample of exoplanets whose stars have well-measured stellar winds. With the addition of chemical models describing chemical processes in an atmosphere, they believe science will eventually get a grip on the energetic particles in other planetary systems.

Observations of exoplanet atmospheres have become common in recent years. Nevertheless, Rodgers-Lee can't wait for the game-changing data from the upcoming James Webb Space Telescope (JWST). "JWST will constrain the chemical abundances in the atmospheres of different types of planets around different stars," she said. "The level of detail will open so many new options."

By **Jure Japelj** (@JureJapelj), Science Writer

Why Are Women More Vulnerable to Flooding in India?

A new study analyzes why women in India are disproportionately affected by flooding. Credit: Varsha Deshpande/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

In India, floods are the most frequently occurring natural hazard, accounting for 47% of all natural disasters and claiming 1,700 lives per year on average. Although studies have shown women to be more vulnerable to natural disasters, so far there is little information on whether or how floods disproportionately affect women in India.

A new study attempts to address this lack of data. The study modeled the impact of floods on gender mortality in India against the inequality-adjusted human development index (IHDI), a measure of inequality in human development. According to the United Nations, "the IHDI combines a country's average achievements in health, education and income with how those achievements are distributed among [the] country's population by 'discounting' each dimension's average value according to its level of inequality."

The authors used state-level data for 19 Indian states from 1983 to 2013, along with household-level data from the India Human Development Survey (IHDS-II) to analyze the social and cultural norms that affect women, such as participation in elections and mobility. Flood mortality data were taken from the National Crime Records Bureau of India for the study period.

The study found that although an increase in IHDI minimized both male and female flood mortality, female mortality was not as reduced as male mortality. Researchers said this difference suggests that inequality in development has a differential impact on women. The study was published in *World Development* (bit.ly/IHDI-natural-disasters).

Joyita Roy Chowdhury, one of the study's authors and an assistant professor of economics at FLAME University in Pune, India, explained the findings by acknowledging that women frequently engage in outdoor farming activities in India: "In rural India, women's involvement in agriculture is substantially high, making women more vulnerable to flood. This is compounded by social norms where women have to take care of children and are unable to move to other occupations."

Neha Pahuja, an Earth science and climate change fellow at The Energy and Resources Institute, Delhi, agreed with Chowdhury. "Because of cultural norms and the inequitable distribution of roles, resources, and power," she wrote via email, "women in India are more vulnerable (to flooding)."

Pahuja, who was not involved in the research, added that the new study reinforced the fact that greater participation of women in political decisionmaking is required to bridge the gap of inequality.

"Women's participation is an indicator of empowerment," Chowdhury said. "When they cast their vote or participate in [village] meetings, they gain information about development policies and how to protect themselves from disasters."

The state of Kerala, for example, has a Gender Equality and Women's Employment Policy that aims to mainstream gender issues in all state policies and projects and provide equal access to resources and economic, social, and political opportunities. One of the points in the policy states that the participation of both men and women will be ensured in programs for environment, conservation, and adaptation to climate change.

Analysis by State

The study modeled the IHDI of each state with flood-related female deaths. The northern state of Bihar had the lowest IHDI and the second-largest number of female deaths from floods. (The more populous state of Maharashtra had the highest number of flood-related female deaths.) Bihar is India's most flood-prone state, and there are reports that rehabilitation programs do not provide adequate relief material to women (bit.ly/flooding-women-rehab-programs).

"Some states like Kerala have a budget for women specifically. When there is a higher expenditure on empowering women, they know how to access information, how to communicate with outsiders."

Vidya Soundarajan, a climate finance expert at WWF India who was not involved in the

study, said via email that "there are two key aspects of the flood impact on women in Bihar. [First,] since open defecation is still quite prevalent, it becomes nearly impossible for women to find a safe place to defecate, which leads to numerous health issues."

Second, she added, men leave for urban areas in search of jobs because of recurrent floods and related agricultural losses, leaving women in villages even more vulnerable.

Soundarajan said that creation of toilets on higher ground in flood-prone areas, job opportunities, and early-warning systems could help mitigate the impact of flooding on women.

Kerala, the state with the highest IHDI, was found to have the lowest number of female deaths from floods. Chowdhury attributed this to policies aimed directly at women. "Some states like Kerala have a budget for women specifically," she said. "When there is a higher expenditure on empowering women, they know how to access information, how to communicate with outsiders."

In addition to the Gender Equality and Women's Employment Policy, for example, Kerala also established a Kudumbashree scheme to empower poor women. In the program (named from the Malayalam for "prosperity of the family"), women from lower economic strata participate in neighborhood or community group meetings to further developmental goals and secure economic opportunities. Leadership roles are held by women on a rotating basis, ensuring that all women members get a chance at leadership. Policies like these do not directly affect mortality but have an indirect impact, Chowdhury explained. Pahuja added that when women are in control of resources, they are more likely to adapt strategies in response to information and make decisions that minimize risk.

Adaptation to climate change depends on one's capability to cope and recover. With extreme weather conditions such as floods expected to increase, "it is imperative that gender equality and women's empowerment continue to influence, shape, and drive the collective climate and human development effort," said Pahuja.

By **Deepa Padmanaban** (@deepa_padma), Science Writer

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Red Rocks: Using Color to Understand Climate Change

The Chinle Formation at Petrified Forest National Park provides a "living laboratory" for studying the Triassic period. Credit: National Park Service

Reddish rock formations pervade the American Southwest. Their coloration is associated with the mineral hematite, through which a recent Rutgers University–led study uncovered a powerful link to climate.

According to lead author Christopher Lepre, conventional understanding attributes redness in the rock formations to diagenesis, a process of oxidation that occurs well after rocks are formed. Lepre's team asked whether the coloration was due not to diagenesis but to a different process altogether. Lepre is an assistant instructor in Earth and planetary sciences at Rutgers.

"My coauthor, Paul Olsen, and his colleagues demonstrated some years ago that the color changes in Triassic rocks from the Newark Basin in New Jersey correlate with ancient monsoonal climate changes," said Lepre (bit.ly/Triassic-rock-climate-change). Applying that correlation to rocks on the Colorado Plateau, Lepre's team identified a healthy concentration of similarly ancient, colored hematite. "That revises how we start to think about how these rocks got these wonderful colors."

Celina A. Suarez, an associate professor in the Department of Geosciences at the University of Arkansas not involved in the new research, called the study "a really interesting application."

"Diagenesis is such an amorphous term that researchers tend to shy away from," she said. "Chris saw a pattern in the 'redness data' and thought about what it really means. There is a pattern that correlates with other proxy patterns related to precipitation, and he dug into it [to] find what controls hematite formation.... Nobody's ever thought about using hematite as a paleoproxy for understanding seasonal climate parameters like precipitation."

Climate Impacts on Seasonality, Paleontology

Lepre and his colleagues examined part of a 518-meter-long rock core from the Chinle Formation in Petrified Forest National Park in Arizona. Using diffuse reflectance spectroscopy, they obtained the wavelengths of various colors to find the concentration of hematite as well as grain size, which causes the color to be more blue or red. (A more arid climate corresponds to a more reddish hue.) By looking at color cycles recorded in the rock formations, the team evaluated climate

behavior during the Late Triassic, about 216 million to 213 million years ago.

Morgan Schaller, an associate professor at Rensselaer Polytechnic Institute not involved with the study, noted the importance of the work: "There are scant few mechanisms of determining hydrological conditions like rainfall on the ancient Earth, especially ones that have the potential to be calibrated quantitatively with so few confounding controls."

In addition to understanding climate change in the Late Triassic, the new data might be used to imagine how future climate changes might affect monsoonal environments. "Atmospheric [carbon dioxide] levels were very high in the Late Triassic—this is probably not analogous to what's going to happen in our lifetime but is certainly relevant for [future] projections," Lepre said.

Suarez said the new research also has a strong impact on understanding seasonality. "That's something that a lot of paleoclimatologists are grappling with," she said. "If you can apply this [methodology] to multiple other climate crises throughout Earth's history, it has the potential for being highly impactful for understanding climate change impacts on extreme seasonality."

Bill Parker, chief scientist at Petrified Forest National Park, was interested in applying lessons from the study to paleontology: "The ability of dinosaurs over other animal groups to thrive through the climatic effects from the Triassic probably was a major factor of [their] success, and we need to [learn] more about the effects of climate on animal populations."

The new study was published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/climate-late-Triassic).

Mentorship and Collaboration with the Navajo Nation

Although this study took place on federal land, part of the project's sequel proposes coring on Navajo lands, opening the door to deepening an ongoing relationship between outside geologists and the Navajo Nation. Although COVID-19 disrupted plans for in-person collaboration and virtual meetings are difficult because of a lack of Internet access, the research team has formed a working group of seven scientists, including three members of the Navajo Nation, who have been meeting virtually.

One member of this working group, Lavina Becenti, is a geologist with the Navajo Nation. "My involvement is to speak to the community and to tell them how this will affect the Navajo Nation," Becenti said. "It brings underrepresented minority students from community colleges on the Navajo reservation to opportunities they wouldn't find anywhere else.... There is a lot of interest from students, and they learn a lot, present at conferences, and talk to their local community."

Becenti also mentioned that the project would be used to find viable aquifers, a crucial task, as the pandemic has exacerbated water scarcity. Additional concerns include testing for soil and water quality, understanding how climate change will affect the Southwest, and expanding youth training opportunities. In addition, undergraduate students are setting up a website in Navajo that communicates the recent findings to the community. It is scheduled to go live soon, and Becenti noted that the team has plans to speak to the community as the pandemic comes to a close.

"As the nation begins to open up, we will hold town halls and invite the Navajo community to join our project as consultants and scientists," Lepre said. "There are a lot of opportunities to get young people involved—not just because of the environmental implications for their own communities, but because it's exciting stuff."

"We are looking forward to continued partnership with tribal members that has been ongoing since 2009," said Jessica Whiteside, an associate professor of ocean and Earth sciences at the University of Southampton. Whiteside has worked with the Navajo Nation on similar projects and is a co-principal investigator on the current project's sequel. "We have plans for a cross-cultural field school setting, science communication workshops, and continued internship programs."

"There's an old saying when you do fieldwork: You take only pictures and you leave only footsteps," recalled Lepre. "But I think we can leave something besides footsteps—make relationships, bring some science that takes root there and is managed by the people rather than outsiders like us."

By **Ria Mazumdar** (@riamaz), Science Writer

Amazon Forests Are Turning into Savannas

Wildfires in the Amazon's Rio Negro floodplain, which leave scars like this one, are changing the ecosystem from forest to savanna, according to new research. Credit: Google Earth

If the Amazonian climate becomes drier and fires become more frequent, floodplain forests in the Amazon basin may change to new ecosystems, according to new research.

Scientists studied 40 years of wildfire history in the seasonally flooded forests of the middle course of the Rio Negro, an area of about 4,100 square kilometers in the central Amazon.

They concluded that when these forests are repeatedly disturbed by wildfires, the soil gradually loses both clay and nutrients and becomes increasingly sandy. Simultaneously, the paper notes, "native herbaceous cover expands, forest tree species disappear and white-sand savanna tree species become dominant." The research was published in *Ecosystems* (bit.ly/wildfire-sandy-soil).

Floodplain Forests Already at Risk

Floodplain forests like those in the Rio Negro area are seasonally flooded ecosystems. The river mitigates damage from wildfires and contributes to the development of root mats—well-aerated plant roots and leaf litter that lie above the soil—which reduce water infiltration. As droughts become more frequent and severe, seasonal rains become less dependable, and root mats become a fire hazard. In fact, said Bruce Walker Nelson, a staff researcher at the Instituto Nacional de Pesquisas da Amazônia in Brazil, the single biggest reason floodplain forests burn so easily is the fact that during dry periods, root mats become "a fine fuel that dries quickly and burns easily." Nelson was not involved in the new research.

"Studies have suggested that these [regrown] forests hold 25% less carbon than primary forests which have never been affected by fires," said Liana O. Anderson, a researcher at the National Centre for Monitoring and Early Warning of Natural Disasters in Brazil not involved in the new study. This degraded capacity to store carbon persists for a long time. "Even after 30 years of fires, these forests don't recover," she added.

Transition to Savanna

The researchers analyzed Landsat images of forested areas for wildfires between 1973 and 2014. Bernardo M. Flores, a researcher at the Federal University of Santa Catarina in Brazil and lead author of the new paper, explained that over those 40 years, around 100 square kilometers of the Rio Negro region burned at least once. In addition, in 2015–2016, data reflected an anomaly: the strongest El Niño in 100 years. This weather phenomenon brought extreme droughts to the region and is associated with the burning of around 700 square kilometers.

Analysis of the Landsat data revealed the growing presence of white-sand savannas, a naturally occurring grassland ecosystem in the region. White-sand savannas are like "islands surrounded by forest across the Amazon," Flores said. He added that these ecosystems have expanded over forests in the past, and the new study shows that "wildfires are a mechanism that can facilitate these expansions."

"Long-term, progressive conversion to nonforest has already occurred in the fertile floodplain of the more densely occupied parts of the Amazon main stem," Nelson said. Now, he added, "Bernardo has shown that even the remote floodplains of nutrient-poor blackwater rivers, with very low population density, can go the same route."

The conversion of forest to savanna has atmospheric and biological implications: In addition to being greater carbon sinks than grasslands, forests also control soil erosion and maintain water quality. These ecosystem services "increase the abundance of fish and other resources for local communities," Flores said.

Climate Change and Declining Resilience to Wildfires

By bringing warmer temperatures and more severe weather, climate emergency "is changing fire regimes across the world. Wildfires are becoming more severe. And in the tropics, forests are shrinking because of deforestation and wildfires," Flores said.

Anderson, too, stressed the need to incorporate climate data when modeling the future of the rain forest. "We need to think about climate change projections because with higher temperatures and lower rainfall, there is greater stress on both these [burned] forests and primary forests," she explained.

By **Rishika Pardikar** (@rishpardikar), Science Writer

Building a Better Model to View Earth's Interacting Processes

Earth's climate is the result of a complex network of interacting systems: air currents, ocean biogeochemistry, mountain ranges, and ice sheets, to name a few. Understanding how our climate evolves and predicting what it will look like under various scenarios require comparing and combining multiple models and simulations, each with its own strengths and focus areas. Earth science researchers are currently putting the most recent release of one such modeling system through its paces.

The open-source Community Earth System Model (CESM) modeling framework is used for many purposes, including in investigations of past and current climate, projections of future climate change, and subseasonal-to-decadal Earth system predictions. Its latest version, CESM2, was released in June 2018, followed by several incremental releases that included additional, readily available model configurations. Compared with its predecessor, CESM2 offers researchers new capabilities, including more realistic representations of changes in Greenland's ice sheet and interactions of agricultural crops with the Earth system, as well as detailed models of clouds and wind-driven ocean waves.

Part of the sprawling Greenland Ice Sheet is seen in this aerial view. Credit: Tim Bocek, CC BY-NC-SA 2.0 (bit.ly/ccbyncsa2-0)

A Community Effort

CESM is a collaborative modeling effort involving researchers at the National Center for Atmospheric Research (NCAR), various universities, and other national and international research institutions. CESM2 component models include the atmosphere, land, ocean, sea ice, land ice, rivers, and ocean waves, all of which use a coupler to exchange information about fluxes (e.g., latent and sensible heat, shortwave radiation, precipitation) and states (e.g., surface temperatures) with each other.

The atmospheric component model has both a low-top and a high-top version. The low-top version accounts only for effects below the stratopause (the boundary between the stratosphere and the mesosphere) and has limited chemistry capabilities, including a relatively coarse stratospheric representation and no prognostic chemistry for ozone and other stratospheric constituents. The high-top version includes the stratosphere and extends above the stratopause. This version's comprehensive chemistry capabilities include a better stratospheric representation, with chemical mechanisms for more than 200 species represented. CESM participants performed numerous simulations with both high- and low-top versions to support CESM's contributions to the Coupled Model Intercomparison Project Phase 6 (CMIP6) [*Eyring et al.*, 2016].

CESM simulations are widely used in many studies, including in national and international climate assessments.

In addition to the Diagnostic, Evaluation and Characterization of Klima (DECK) experiments (four standard simulations required for participation in CMIP), CESM2 participated in about 20 CMIP6-endorsed Model Intercomparison Project (MIP) efforts. Most of these simulations were performed using 1° horizontal spatial resolution in all component models. To provide a computationally more economical model for long timescales (e.g., for paleoclimate applications), we also conducted several DECK and MIP simulations with a version that uses a coarser 2° horizontal resolution in its atmospheric component.

Because CESM simulations are widely used in many studies, including in national and international climate assessments, it is important that the model's main characteristics are thoroughly analyzed and documented. Thus, articles describing and analyzing these CESM2 CMIP6 experiments in detail are collected in the AGU CESM2 virtual special issue, which spans several AGU journals (bit.ly/AGU-CESM2).

Overcoming Obstacles

We encountered two major challenges during the development of CESM2. First, our control simulations of preindustrial conditions

This snapshot of winds over the Greenland Ice Sheet was taken from a simulation run using a configuration of the atmospheric component of the second version of the Community Earth System Model with 1/8° spatial resolution. Wind streamlines at the lowest model level are colored according to wind speed (warmer colors indicate faster winds). Katabatic winds, in which gravity carries high-density air masses downward, can be seen accelerating down the eastern slopes of the ice sheet. This image was inspired by a visualization of winds over Antarctica by the Polar Meteorology Group at the Byrd Polar and Climate Research Center. Credit: Matt Rehme and Adam Herrington, NCAR

CESM2 still has shortcomings, including local precipitation biases, larger-than-observed ENSO amplitudes, thin Arctic sea ice in some simulations, and some other persistent biases.

showed the formation of unrealistically extensive sea ice cover in the Labrador Sea region. Second, global mean surface temperature time series in historical simulations displayed unrealistic cooling during the second half of the 20th century [*Danabasoglu et al.*, 2020].

Considerable analysis of model simulations did not identify a particular culprit for the emergence of extensive sea ice cover. However, we found that extremely small perturbations in model fields could trigger this behavior in some ensemble simulations that were otherwise identical to simulations that did not show the same sea ice development. Thus, a practical solution was simply to use initial conditions for the ocean and sea ice from an ensemble member that did not produce such an extensive sea ice cover in the Labrador Sea.

Because aerosol particles can affect clouds and their radiative properties, we addressed the problem of unrealistic cooling in the simulations by introducing minor modifications to the representation of aerosol-cloud interaction processes in the CESM2 atmospheric component. These modifications were aimed at reducing the excessive influence of aerosols on the liquid water path (the total amount of liquid water between two points in the atmosphere) in comparison with observations. These changes produced an acceptable simulation of the surface temperature time series during the 20th century.

The data sets from CESM2 CMIP6 simulations are available from the Earth System Grid Federation (ESGF). To date, CESM participants have run about a thousand CMIP6 experiments—including some tier 2 simulations for several MIPs (tier 1 represents the highest-priority experiments)—and about 600 terabytes of data have been published on the ESGF. This volume of data is roughly 7 times larger than CESM1 contributions to CMIP Phase 5.

New Features and Findings

An introduction to CESM2 [*Danabasoglu et al.*, 2020] summarizes many new scientific and technical advances in CESM2 compared with its predecessor, CESM1. Among many others, these advances include improved representations of clouds [*Golaz et al.*, 2002], crops [*Lawrence et al.*, 2019], and Greenland's evolving ice sheet [*Lipscomb et al.*, 2019].

Compared with available observations and with CESM1, CESM2 historical simulations show reduced biases for precipitation and shortwave cloud forcing. CESM2 simulates many aspects of the El Niño–Southern Oscillation (ENSO) well, including its dominant, multiyear timescale and associated teleconnections that affect, for example, precipitation and surface pressure and temperatures [*Capotondi et al.*, 2020]. The same is true for the Madden-Julian Oscillation [*Danabasoglu et al.*, 2020]. In addition, CESM2 significantly improves representations of storm tracks, Northern Hemisphere stationary waves (planetary-scale variations in atmospheric circulation), and winter blocking (obstructions of weather systems that can produce extreme weather events at lower latitudes) [*Simpson et al.*, 2020]. Despite these improvements, CESM2 still has shortcomings. These include local precipitation biases, larger-than-observed ENSO amplitudes, thin Arctic sea ice in some simulations, and some other persistent biases such as an incorrect path of the North Atlantic Current.

The equilibrium climate sensitivity (ECS) and the transient climate response (TCR) are two properties that emerge from the coupled simulations. ECS represents the equilibrium change in global mean surface temperature after a doubling of atmospheric carbon dioxide (CO_2), and TCR represents the change in global mean surface temperature around the time of CO_2 doubling when CO_2 increases by 1% per year.

CESM2 ECS values of 5.1°C–5.3°C are considerably higher than those produced by its previous versions, which had ECS values of about 4.0°C. Models that generate higher ECS values predict more climate warming for a given amount of atmospheric CO_2 than models that generate lower ECS values. The increased ECS in CESM2 is largely due to a combination of relatively small changes in cloud microphysics and boundary layer

parameters, resulting in changes in clouds and their feedbacks, particularly over the Southern Ocean but also over the tropical oceans [*Bacmeister et al.*, 2020; *Zelinka et al.*, 2020; *Gettelman et al.*, 2019]. In contrast, TCR values in CESM2 remain at about 1.9°C–2.0°C, similar to those in previous versions. The consistency in this globally integrated value, however, masks significant regional differences in warming magnitude and patterns in CESM2 with respect to CESM1 [*Bacmeister et al.*, 2020].

CESM2 does not appear to be alone in exhibiting an increased ECS. Indeed, one third of the CMIP6 generation models (13 out of 39) studied by *Meehl et al.* [2020] have ECS values higher than 4.5°C, with 6 of the models showing even higher values of more than 5°C. (The Intergovernmental Panel on Climate Change has previously cited a "likely" ECS range of 1.5°C–4.5°C.) These researchers also report a range of 1.8°C–5.6°C for ECS in these new generation models. Both this range and the high ECS values in CMIP6 are significantly greater than those seen in previous generation models. *Meehl et al.* [2020] identified cloud feedbacks and cloud-aerosol interactions as the likely contributors to increased ECS in the new generation of models—as was the case for CESM2—with the details of sensitivities possibly differing among models.

Anticipating Advances to Come

Although CESM2 has been used primarily for CMIP6-related simulations and applications so far, its use will continue to expand for many years to come. One such effort is the new CESM2 Large Ensemble, a suite of simulations of the 1850–2100 time period, each starting with slightly different initial states. This effort is being performed in collaboration with the Institute for Basic Science Center for Climate Physics in Busan, South Korea. This 100-member model ensemble is expected to be available to the community in summer 2021. Additional ensemble members that isolate the effects of forcings will also be available. Another upcoming effort is a new set of CESM2 subseasonal-to-decadal prediction simulations.

The AGU CESM2 virtual special issue articles highlight many improvements in model solutions and advances in our scientific understanding with CESM2. Some early analyses also suggest that CESM2 simulations rank among the best coupled models in the CMIP6 archive in comparison with observation-based metrics (e.g., metrics associated with energy and water cycles and atmospheric dynamics) [*Fasullo*, 2020].

We anticipate that some of the biases and shortcomings in CESM2 will be addressed as we move toward our next-generation model, CESM3, an effort that has already started.

As noted above, CESM2 still suffers from some biases and shortcomings. We anticipate that some of these biases will be addressed as we move toward our next-generation model, CESM3, an effort that has already started. We plan to incorporate many advances in this next iteration in close collaboration with the Earth system modeling community. Such advances will include a new ocean model component and higher atmospheric vertical resolution available with a new dynamical core.

The virtual special issue is spread across several AGU journals, including *Geophysical Research Letters*, *Global Biogeochemical Cycles*, *Journal of Advances in Modeling Earth Systems*, *Journal of Geophysical Research: Atmospheres*, *Journal of Geophysical Research: Earth Surface*, and *Journal of Geophysical Research: Oceans*. At the time of this publication, members of the Earth system modeling community have contributed about 45 published or submitted manuscripts. And we look forward to more contributions to come, which will continue advancing this modeling effort as well as our understanding of our planet's past, present, and potential future climate.

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CORES 3.0

FUTURE-PROOFING EARTH SCIENCES' HISTORICAL RECORDS

CORE LIBRARIES STORE A TREASURE TROVE OF DATA ABOUT THE PLANET'S PAST. WHAT WILL IT TAKE TO SUSTAIN THEIR FUTURE?

BY JANE PALMER

The main storage room at the National Science Foundation Ice Core Facility currently holds approximately 22,000 meters of ice cores. The room temperature is kept at about –36°C. Credit: NSF Ice Core Facility

n September 2013, a major storm dumped a year's worth of rain on the city of Boulder, Colo., in just 2 days. Walls of water rushed down the mountainsides into Boulder Creek, causing it to burst its banks and flood nearby streets and buildings.

Instead of trying to escape the flood, Tyler Jones, a biogeochemist at the Institute of Arctic and Alpine Research (INSTAAR) in Boulder, drove directly toward it. His motive? Mere meters from the overflowing creek, a large freezer housed the lab's collection of precious ice cores.

"We didn't know if the energy was going to fail in the basement," Jones said. "So I am scrambling around with a headlamp on, less than a hundred yards from a major flood event, trying to figure out what is going on."

The INSTAAR scientists were lucky that year, as their collection survived unscathed. But devastating core culls have happened in the past decade. In a 2017 freezer malfunction at the University of Alberta in Edmonton, Canada, part of the world's largest collection of ice cores from the Canadian Arctic was reduced to puddles. "Thinking of those kinds of instances makes me lose sleep at night," said Lindsay Powers, technical director of the National Science Foundation Ice Core Facility in Denver.

Collections of cores—including ice cores, tree ring cores, lake sediment cores, and permafrost cores—represent the work of generations of scientists and sometimes investments of millions of dollars in infrastructure and field research. They hold vast quantities of data about the planet's history ranging from changes in climate and air quality to the incidence of fires and solar flares. "These materials cover anywhere from decades to centuries and even up to millions of years," said Anders Noren, director of the Facilities for Continental Scientific Drilling and Coring in Minneapolis, which includes a library of core samples. "It's a natural archive and legacy that we all share and can tap into—it's a big deal."

Historically, some individual scientists or groups have amassed core collections, and on occasion, centralized libraries of cores have emerged to house samples. But irrespective of the types of cores stored or their size, these collections have faced a series of growing pains. Consequently, facilities have had to adapt and evolve to keep pace and ensure that their collections are available for equitable scientific research.

"We spend a lot of time in science thinking about open access when it comes to data," said Merritt Turetsky, director of INSTAAR. Scientists should be having simi-

Ice cores stored in the temporary core storage in the underground ice cave constructed by the East Greenland Ice-Core Project. Credit: Tyler R. Jones/ INSTAAR

lar conversations about open access to valuable core samples, she said. “It is important to make science fair.”

CORES AND COOKIES

After 30 years of collecting wood samples for his research, astronomer Andrew Ellicott Douglass founded the Laboratory of Tree-Ring Research (LTRR) in 1937. With its creation at the University of Arizona in Tucson, Douglass formalized the world’s first tree ring library. Its development in the years since is a paradigm for the way core libraries are subject to both luck and strategy.

Dendrochronologists use tools to extract cores from trees to date structures and reconstruct past events such as fire regimes, volcanic activity, and hydrologic cycles. In addition to these narrow cores, they can also saw across tree stumps to get a full cross section of the trunk, called a cookie.

Douglass originally collected cores and cookies to study the cycle of sunspots, as astronomers had observed that the number of these patches on the Sun increased and decreased periodically. The number of sunspots directly affects the brightness of the Sun and, in turn, how much plants and trees grow. By looking at the thickness of the tree rings, Douglass hoped to deduce the number of sunspots in a given year and how that number changed over the years. Douglass also went on to date archaeological samples from the U.S. Southwest using his tree ring techniques. On the way, he amassed an impressive volume of wood.

Douglass’s successors at LTRR were equally fervent in their collection. Thomas Swetnam, the director of LTRR between 2000 and 2014, estimated that his collection of cores and cookies gathered in a single decade occupied about 100 cubic meters.

During the turn of the 20th century, loggers felled a third of the giant sequoias in what is now Sequoia National Park in California. The only upside to the environmental tragedy was that it afforded researchers like Swetnam, who studies past fire regimes, the opportunity to collect cookies. “We were able to go with very large chainsaws and cut slabs of wood out of these sequoia stumps, some of them 30 feet [9 meters] in diameter,” Swetnam said. “Then we would rent a 30-foot U-Haul truck, fill it up, and bring it back to the lab.”

The laboratory’s collection catalogs about 10,000 years of history, Swetnam said. It also amounts to a big space issue. “We’re talking about probably on the order of a million samples, maybe more,” Swetnam said. “We’re not even sure exactly what the total count is.”

The tree ring samples had been temporarily stored under the bleachers of Arizona Stadium in Tucson for nearly 70 years, but with generous funding from a private donor, a new structure was built to house the laboratory and its collection in 2013. The building, shaped like a giant tree house, solved the space issue, and in 2017 the lab received further funding to hire its first curator, who was charged with the gigantean task of organizing more than a hundred years of samples.

At the Laboratory of Tree-Ring Research in Tuscon, Ariz, curators are cataloging a more than a century’s worth of wood samples. Credit: Peter Brewer

“RECOVERING ICE FROM 2 MILES BENEATH AN ICE SHEET IN EXTREME COLD ENVIRONMENTS IS A MASSIVE CHALLENGE. YOU CAN’T JUST GO BACK AND REPEAT THAT.... IT’S A ONE-TIME DEAL.”

Cookies are stacked like books at the Laboratory of Tree-Ring Research in Tuscon, Ariz. Credit: Peter Brewer

(top) Constructing giant trenches at Dome Concordia in Antarctica. Digging these trenches was the first step in trialing how to store ice cores in underground caves. Credit: Armand Patoir, French Polar Institute IPEV (bottom) Ice Memory project scientists extract ice cores at Illimani glacier in Bolivia in 2017 Credit: Sarah Del Ben, Foundation Grenoble Alpes University

"It is a very long term endeavor," said Peter Brewer, the LTRR curator who now works with a 20-person team on the collection. Brewer set to standardizing the labeling for the samples and is the co-lead on an international effort to produce a universal data standard for dendrochronological data. With this in place, LTRR will soon be launching a public portal for its collections, where scientists can log on and request a sample loan. This portal will make the collection more accessible to researchers around the world.

"WE ARE AT WORK HERE PROMOTING CLIMATE RESEARCH, SO WE WANT TO BE USING THE BEST TECHNOLOGY POSSIBLE TO HAVE THE LOWEST IMPACT ON OUR ENVIRONMENT."

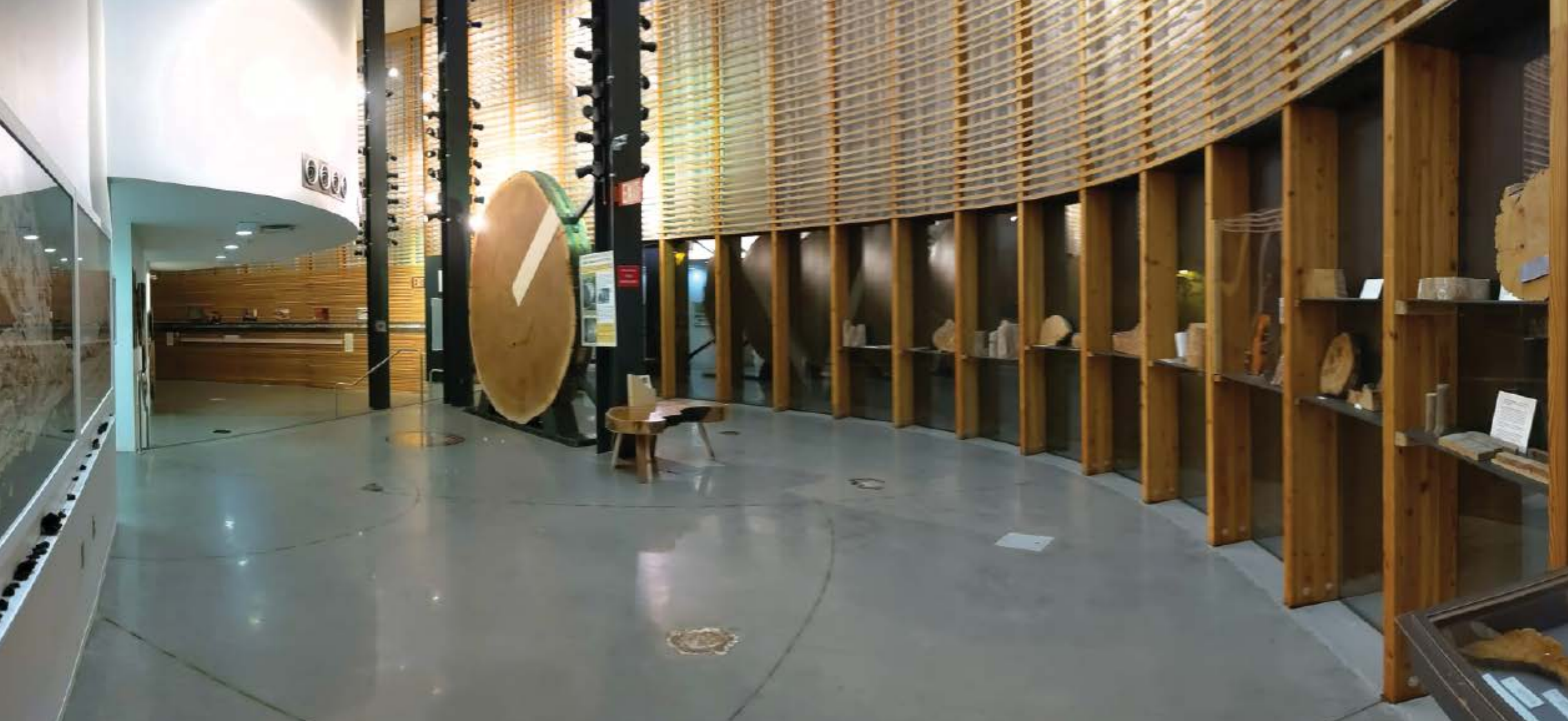
ICE ISSUES

In the early 1900s, around the same time that Douglass was collecting his first wood samples, James E. Church devised a tool to sample ice cores 9 meters below the ground. By the 1950s, scientists were able to extract cores from depths of more than 400 meters in the Greenland Ice Sheet. In the following years, scientists have drilled deeper and deeper to extract and collect ice cores from glaciers around the world.

Ice cores can reveal a slew of information, including data about past climate change and global atmospheric chemistry. "We've learned so much already about environmental challenges from ice cores, and we think that there is so much more to learn," said Patrick Ginot of the Institute of Research for Development at the Institute of Environmental Geosciences in Grenoble, France.

Some labs, such as INSTAAR, maintain their own collections, but space can quickly become an issue, and there's constant concern about keeping the samples frozen and safe. Taking into consideration the massive effort involved in securing a single ice core, each sample is akin to an irreplaceable work of art. "Recovering ice from 2 miles [3.2 kilometers] beneath an ice sheet in extreme cold environments is a massive challenge," Jones said. "You can't just go back and repeat that.... It's a one-time deal."

The National Ice Core Lab in Denver houses many ice cores collected by scientists on National Science Foundation–funded projects. The goal is to provide a fail-safe storage environment and open access to researchers wishing to use the samples. Denver's altitude and low humid-



Cores and cookies are on display at the Laboratory of Tree-Ring Research in Tuscon, Ariz. Credit: Peter Brewer

ity make running the freezers more efficient, and a rolling rack system in a new freezer will increase storage capacity by nearly a third. The facility also has backups galore: "We have redundancy on everything, and everything is alarmed," Powers said.

The carbon footprint of running giant freezers at −36°C is high, but the lab is in the process of installing a new freezer that uses carbon dioxide refrigeration, the most environmentally friendly refrigeration system on the market. "We are at work here promoting climate research, so we want to be using the best technology possible to have the lowest impact on our environment," Powers said.

SCIENCE WITHOUT BORDERS

The ice core community has adapted to various challenges that come with sustaining their libraries and working toward making the samples available on an open-access basis. But other parts of the cryosphere community are still catching up, Turetsky said.

Turetsky collects hundreds of northern soil and permafrost cores each year with her INSTARR team, and scores of other permafrost researchers are amassing equal numbers of cores from across the United States and Canada on a yearly basis. The U.S. permafrost community has more samples than the U.S. ice core community—but still doesn't have a centralized library.

Turetsky said she is looking to learn from the ice core community while recognizing that the challenges are different for permafrost researchers. Because it is easier and less expensive to collect samples, the community hasn't needed to join forces and pool resources in the same way the ice core community has, leading to a more distributed endeavor.

Turetsky's vision is to establish a resource for storing permafrost samples that anyone can tap into, as well as for the U.S. permafrost community to come together to develop guiding principles for the data collected. The University of Alberta's Permafrost Archives Science Laboratory, headed by Duane Froese, is a great example of a multiuser permafrost archive, Turetsky said. Ultimately, the community may need to think about a regional hub with international connections to propel scientific inquiry.

"We can't do our best science siloed by national borders," Turetsky said. "I would love to see sharing of permafrost samples or information be a type of international science diplomacy."

A RACE AGAINST TIME

The need for the cryosphere community (encompassing both ice core and permafrost researchers) to come together and collect data in such a way that they can be shared and used in the future has never been greater, Turetsky said. The Arctic is warming faster than anywhere else on the planet, and simultaneously warming sea ice, ice sheets, and permafrost have great potential to influence Earth's future climate. "So not only are [ice and permafrost environments] the most vulnerable to change, they also

"WE CAN'T DO OUR BEST SCIENCE SILOED BY NATIONAL BORDERS. I WOULD LOVE TO SEE SHARING OF PERMAFROST SAMPLES OR INFORMATION BE A TYPE OF INTERNATIONAL SCIENCE DIPLOMACY."

Tree trunks, cores, and cookies are stored in a humidity-controlled environment at the Laboratory of Tree-Ring Research in Tuscon, Ariz. Credit: Peter Brewer

"A GOOD CHUNK OF WHAT WE HAVE NO LONGER EXISTS IN THE FORESTS. ALL THAT IS LEFT ARE THE REPRESENTATIVE PIECES OF WOOD THAT ARE IN OUR ARCHIVES."

will change and dictate our climate future," Turetsky said.

In the worst-case scenario, the Arctic may lose all sea ice or permafrost, and scientists will lose the ability to collect core samples. "So it is a race against time to get cores, to learn, and to communicate to the public how dire the situation is," Turetsky said.

Tree ring researchers are facing their own race against time, Swetnam said. As wildfires rage across the United States, scientists are trying to collect as much as possible from older trees before they are claimed by flames. "The history that's contained in the rings is not renewable," Swetnam said. "It's there, and if it's lost, it's lost."

That scientists may lose the ability to collect some samples makes maintaining core libraries and sharing their resources all the more important, Brewer said. "A good chunk of what we have no longer exists in the forests. All that is left are the representative pieces of wood that are in our archives."

A FUTURISTIC VISION

Recognizing threats posed by climate change, one group of cryosphere scientists has set out to create a visionary ice core library for future generations. Instead of housing core samples from around the world in one country, the group plans to store them in Antarctica, a continent dedicated to science and peace; the 1959 Antarctic Treaty specifies that "scientific observations and results from Antarctica shall be exchanged and made freely available."

And the ice cores won't be stored in a building. They'll be buried deep in the largest natural freezer of them all: the Antarctic Ice Sheet. This core library will act as a heritage data set, a legacy for future generations of scientists from all over the world. Researchers can access the cores in the interim, especially those taken from glaciers that no longer exist, and the Ice Memory project's organizers are currently addressing how to grant access to the cores in a way that is equitable, as travel to Antarctica is cost prohibitive for many researchers.

The first stage of the project has focused on how to store the cores in the ice sheet. The plan is to store them about 10 meters deep, where the temperature is a stable −50°C throughout the year. "Even if there are a few degrees of warming in the next decades or centuries, it will still be kept at minus 50° or 45°," said Ginot, one of the coordinators of the Ice Memory project.

Researchers from the French and Italian polar institutes have already trialed the best storage techniques on Dome Concordia in Antarctica. They dug 8-meter-deep, 100-meter-long trenches and inserted giant sausage-shaped balloons on the ice floors. Then they used the dug-out snow to cover the balloons and allowed the snow to harden. "When they disassembled the sausage, they had a cave under the snow," Ginot said.

The project's models forecast that the cavities will last for 20–30 years, at which time the scientists will create more caves at a minimal cost, Ginot said. The current focus of the team is to collect samples from glaciers that are quickly disappearing, such as the northern ice field near the summit of Mount Kilimanjaro in Tanzania.

RECOGNIZING THE VALUE

Core libraries provide a vital window into events that happened before human records began, a repository for data to better understand Earth systems, and resources to help forecast future scenarios. Researchers believe that as science and technology evolve, they'll be able to extract even more information from core collections. "We recognize that this is a library of information, and we've just read some of the pages of some of the books," Swetnam said. "But as long as the books are still there, we can go back and interrogate them."

While the libraries for ice, tree ring, and sediment cores are maintained, scientists are able to access the "books" for further analysis whenever they want.

"We see all kinds of cases where a new analytical technique becomes available, and people can ask new questions of these materials without having to go and collect them in the field," Noren said. New analytical techniques have led to more accurate reconstruction of past temperatures from lake core sediments, for example, and by integrating several core data sets, scientists have revealed that humans began accelerating soil erosion 4,000 years ago.

The multifaceted value of the core collections has become even more pronounced during the COVID-19 pandemic, Noren said. Core libraries have allowed scientists to continue moving forward with their research even when they can't do fieldwork. As recently as March 2021, for example, scientists published research on the multimillion-year-old record of Greenland vegetation and glacial history that was based on existing cores, not those collected by the scientists' field research.

Although some libraries struggle with space constraints, maintaining suitable environmental conditions, cataloging samples, or ensuring open access, every scientist or curator of a core collection shares one concern: sustaining funding.

It costs money to run a core library: money to house samples, money to employ curators, and money to build systems that allow equal and fair access to data. Securing that financial support is a challenge. "Funding priority is about exciting research or a new instrument," Brewer said. "Updating or maintaining a collection of scientific samples is not such an easy sell."

At the National Science Foundation Ice Core Facility, researchers cut samples retrieved from the South Pole Ice Core project to send off to the collaborating universities for analysis. Credit: NSF-Ice Core Facility

Core libraries represent millions of years of history and hold keys to understanding and protecting Earth's future. They are natural archives of ice-covered continents, forested lands, and ancient cultures. As such, they are a legacy to be preserved and protected for future generations, Noren said. "But if you view it from another lens, they are just storage," he explained. "So we need to elevate that conversation and make it clear that these materials are essential for science."

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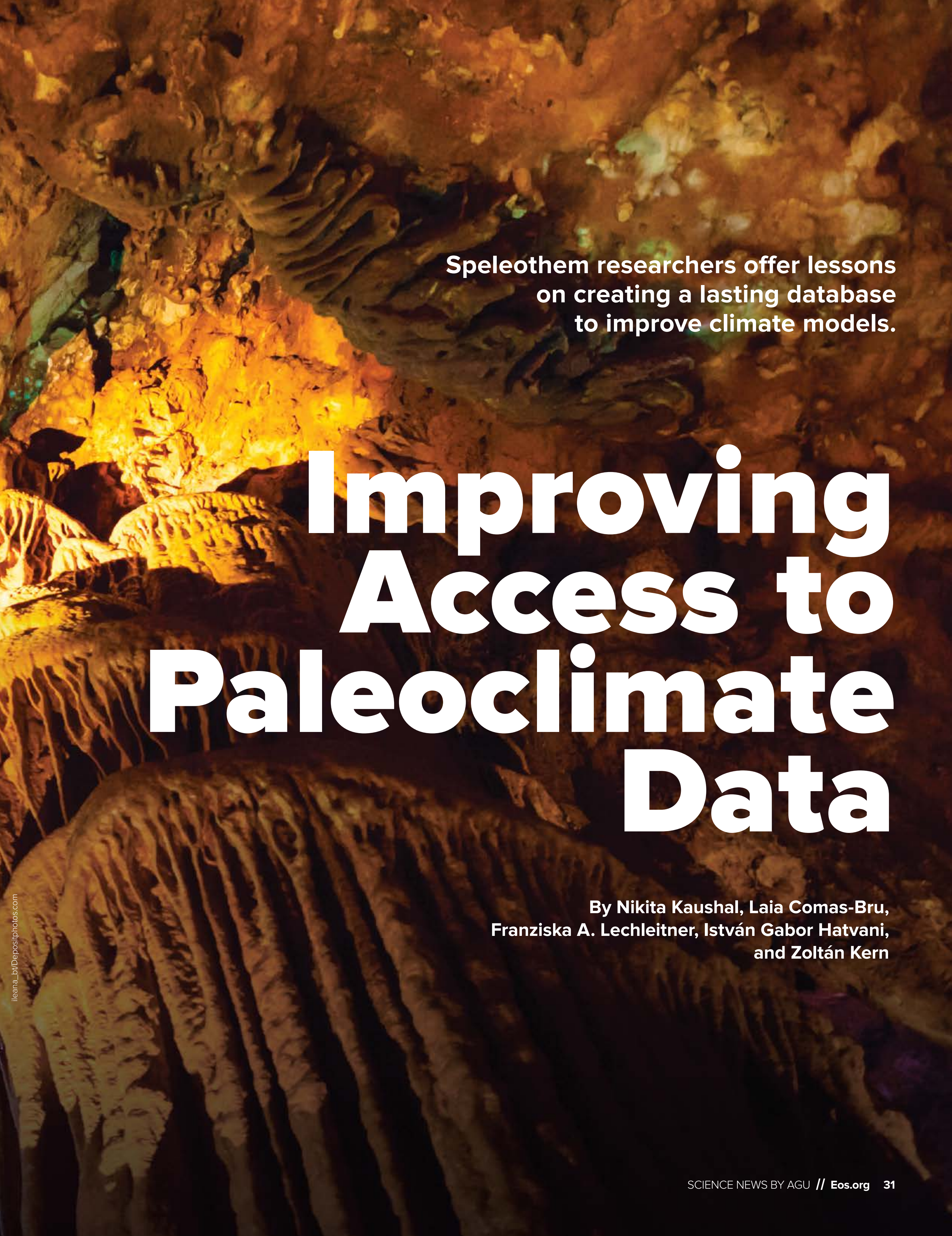

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Speleothem researchers offer lessons on creating a lasting database to improve climate models.

Improving Access to Paleoclimate Data

By Nikita Kaushal, Laia Comas-Bru, Franziska A. Lechleitner, István Gabor Hatvani, and Zoltán Kern

Speleothems adorn a cave near Ioannina, Greece. Natural archives like speleothems can be used to investigate climate variability over the past 600,000 years. Credit: Konstantinos Kourtidis (distributed via imaggeo.egu.eu), CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Earth's climate was substantially more varied in the past than it is today. During the Paleocene-Eocene Thermal Maximum about 56 million years ago, for example, global temperatures were far warmer than today. Similarly, temperatures between about 4,000 and 8,000 years ago, during the mid-Holocene, were also elevated by several degrees on average. On the other hand, during the Little Ice Age, which lasted roughly from the 16th through the 19th centuries, much of the Northern Hemisphere was cooler than today.

Scientists study past climates using different types of paleoclimate data to better understand the planet's range of behavior, which informs our ideas about how it's likely to change in the future. Vast amounts of paleoclimate data have been collected over the past 4 decades from a variety of sources, such as marine sediments, speleothems, ice cores, and tree rings. When such multitudinous data are organized into research databases rather than being maintained as numerous individual data sets, they allow for more accurate reconstruction of past global climate variability and improve the predictive power of models of future climate. However, as academic incentives for those who collect these data are geared toward publication—and not the creation of robust databases—database creation is usually done by researchers on a volunteer basis. Thus, it is important to maximize gains from such efforts.

A number of ongoing efforts are enabling paleoclimate databases, such as the LinkedEarth Project, the Past Global Changes (PAGES) working groups, and the research community–curated data sets in the Neotoma Paleoecology Database. These initiatives face common challenges, among them, (1) deciding on consistent terminology and the essential metadata to be measured and reported, (2) determining how (and how often) to disseminate and update this information, and (3) determining how the continuity of this process can be ensured beyond time-bound funding cycles. Past efforts have tackled these problems using different strategies. In creating a new speleothem database, the speleothem community can provide useful insights to aid in the development of additional paleoclimate databases.

Paleoclimate Proxies in Speleothems

Speleothems are inorganic cave deposits, such as stalagmites and stalactites, that form from drip waters supersaturated with calcium carbonate. They are powerful climate archives because they are found in terrestrial regions around the world and yield information on the climatic and environmental conditions that prevailed during their formation. Scientists can accurately determine speleothem ages by studying the ratios of uranium and thorium isotopes they contain, and speleothems provide robust oxygen isotopic signatures that can be directly correlated with the isotopic signatures of precipitation falling above the cave, allowing reconstructions of regional atmospheric circulation patterns.

In 2017, the Speleothem Isotopes Synthesis and Analysis (SISAL) Working Group was created under the umbrella of PAGES to generate a paleoclimate database based on 4 decades of speleothem paleoclimate research. The first version of the SISAL database was published in 2018 [*Atsawawaranunt et al.*, 2018]; version 2 of the database, published in 2020, contains 691 records, 513 of which have additional standardized age-depth models [*Comas-Bru et al.*, 2020] (Figure 1). (Age-depth models attribute an age to every sample taken along a speleothem's growth axis.)

In speleothem paleoclimate research, individual research groups study stalagmites to target specific climate questions. This approach allows for great flexibility in targeting novel and unconventional research questions. But global, community-wide efforts to synthesize speleothem data and to produce oxygen isotopic maps of

past climate states like the mid-Holocene and the Little Ice Age have been lacking.

These climate states were dominated by specific climate forcings, such as high levels of insolation or profuse volcanic eruptions. Comparing real-world speleothem oxygen isotopic measurements with the results of climate model simulations helps identify shortcomings in the models and ultimately improves their accuracy. Such improvements are crucial, because models that represent past climate states realistically are better able to project future climate change.

Quality Control and Data Standardization

The ultimate aim of a database is to increase the ease with which a large collection of data can be accessed and used to answer research questions requiring regional or global perspectives. Before speleothem oxygen isotopic data can be used in global climate models, individual speleothem data sets must be synthesized and standardized. This process involves organizing the data with standard metadata terminology and standard reporting guidelines [e.g., *Khider et al.*, 2019]. In addition, the data entered in the database must be accurate.

One of the selling points of SISAL's database is that all raw data are first entered into preset data spreadsheets—by the original authors whenever possible—and then quality checked at multiple levels by SISAL coordinators and leaders to avoid data entry mistakes and for metadata completeness before the data are added to the database. Automated scripts that detect common mistakes (e.g., incorrect units of measurement) help in this process. SISAL also disseminates automated unit conversion sheets for data fields such as location coordinates and dating constants to reduce errors and improve standardization. In sum, these approaches help ensure that the SISAL database contains more comprehensive data and metadata than are typically available in public data repositories, such as NOAA's National Centers for Environmental Information (NCEI), which do not have SISAL's extensive data, metadata, and standardization requirements.

Vast amounts of paleoclimate data have been collected over the past 4 decades from a variety of sources, such as marine sediments, speleothems, ice cores, and tree rings.

Scientists in the paleoclimate research community can follow different strategies to achieve metadata and data standardization, making decisions, for example, through open-access voting (e.g., as in the Future Earth Project and the Paleoclimate Community Reporting Standard) or through working groups that decide on equivalent terms to be used across archives (e.g., the PAGES 2k project). The SISAL Working Group selected its initial data and metadata fields, terminology, and reporting standards on the basis of input from active speleothem researchers during a workshop in 2017 [*Comas-Bru et al.*, 2017]. The workshop involved established experts in the field and early-career researchers from groups around the world, and in the end, input from about 100 researchers was considered until the database structure was finalized.

Since SISAL's inception and the creation of the first database, members of the working group using the database have published research papers rapidly [e.g., *Comas-Bru et al.*, 2019]. This consistent data usage has resulted in additional quality control before database publication. The database also allows for identification of metadata fields that are not systematically reported by

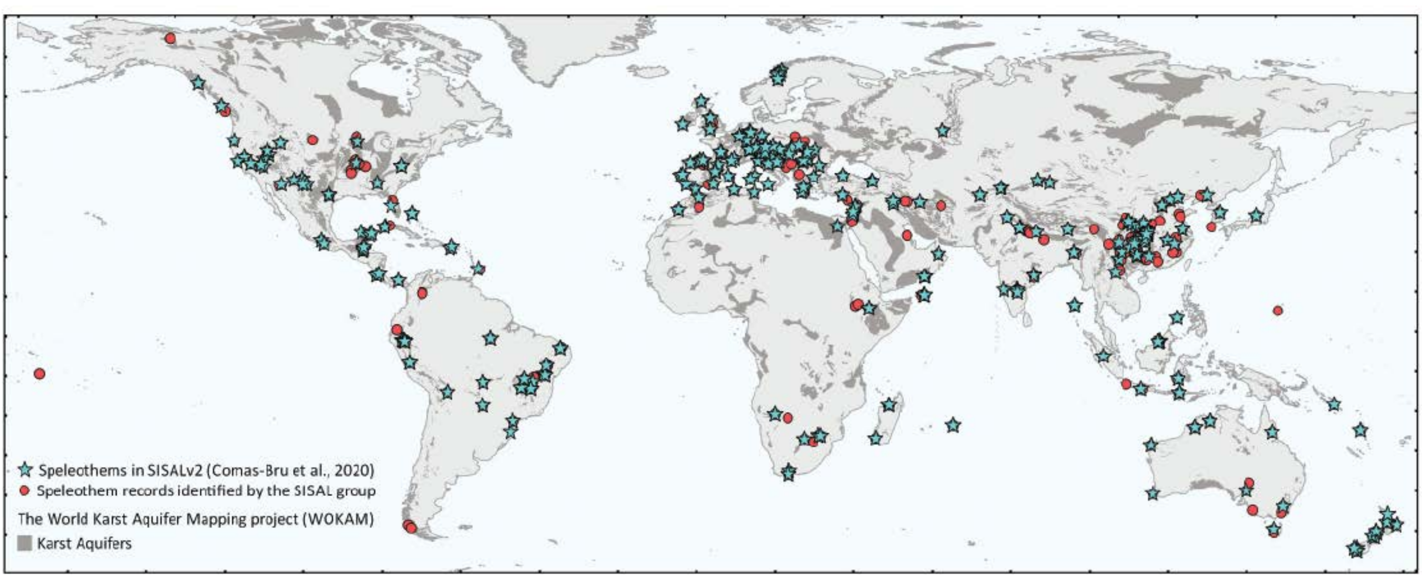


*Fig. 1. Version 2 of the Speleothem Isotopes Synthesis and Analysis (SISAL) database contains 691 speleothem records from 294 cave sites around the world [*Comas-Bru et al., *2020]. The spatial distribution of karst aquifers from* Goldscheider et al. *[2020] is also shown.*

SISAL has reached out beyond the speleothem community and established collaborations with researchers from other paleoclimate disciplines.

researchers but that are necessary for reuse of the data (Table 1). For example, a researcher using the database could screen for speleothem samples with "unknown" mineralogy and then discard these samples from further analysis.

As SISAL is part of a growing number of paleoclimate databases, it is important to consider data and metadata field standardization across platforms to ensure the future continuity and usefulness of these databases. This cross-platform standardization requires a complementary approach involving long-term discussions among data generators, database managers, and the wider research communities involved, with simultaneous tracking of the data being generated and actually used for research.

Fruitful Collaborations

SISAL has reached out beyond the speleothem community and established collaborations with researchers from other paleoclimate disciplines. Particularly noteworthy is the success the working group has had in strategizing with members of the climate modeling community about uses of SISAL data in data-model comparison studies [*Ait Brahim et al.*, 2020]. This exchange has proven exceptionally fruitful for both sides and resulted in open dialogue about what spatiotemporal distributions of speleothem data are useful for modelers and, conversely, how model results can be interpreted and reconciled with the available speleothem data. For example, speleothem data in the SISAL database covering the mid-Holocene have allowed scientists to examine whether climate models accurately account for insolation forcing during this time [*Cauquoin et al.*, 2019].

Collaborations among early-career researchers in the United States and around the world have proved very successful. SISAL, which has been led, coordinated, and implemented by early-career researchers, engaged scientists representing geographical diversity and in different phases of their academic careers to ensure wide accessibility and participation. Selections of workshop participants have been made on the basis of individuals' subject expertise and geographical reach and have actively encouraged early-career researchers to lead and participate in SISAL's efforts. We found that this approach created opportunities for early-career researchers, allowing them to stay up to date with the field and to work on internationally collaborative projects that advance both research in the field and their personal career goals. In addition, data generators and SISAL members involved in the quality-checking process get authorship in SISAL database papers, incentivizing data sharing that leads to a more comprehensive database.

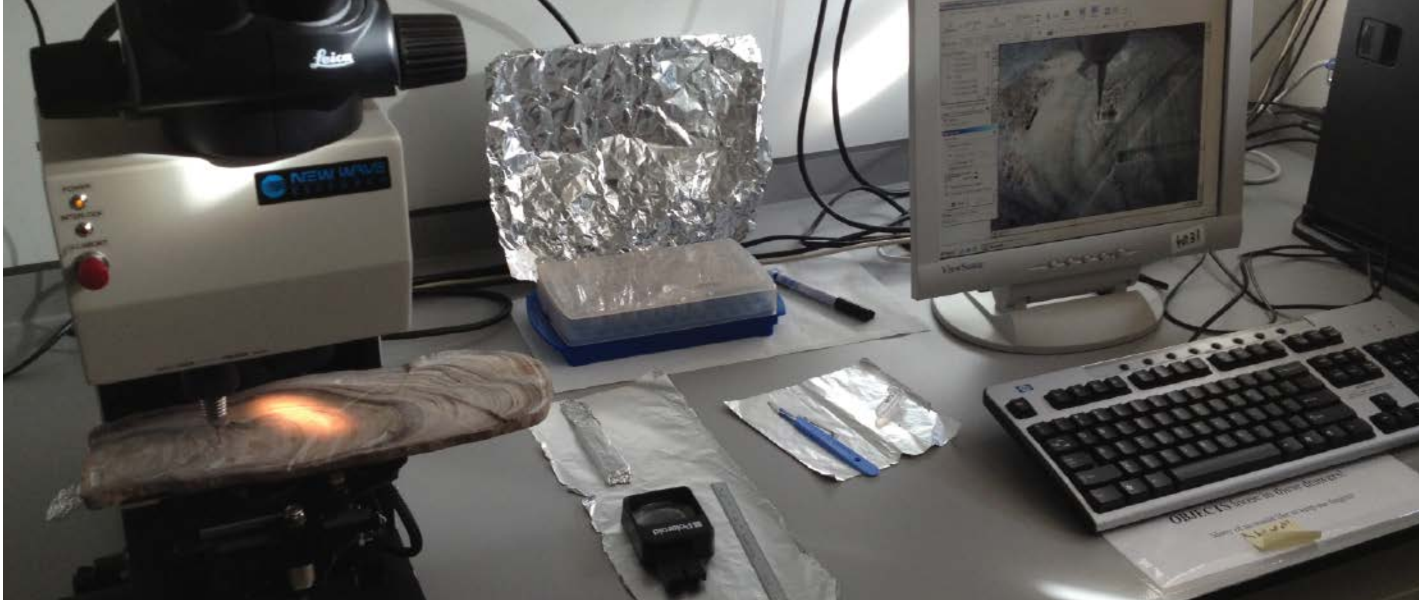
SISAL workshops and collaborative projects have provided opportunities for researchers to develop a "database mindset," which further incentivizes data standardization starting in the early stages of project design. SISAL is a relational database providing data in multiple file types (i.e., CSV and SQL) that can be mined using Python, R, MATLAB, and MySQL, among other programs. Many paleoclimate researchers are new to database querying and even to the idea of framing research questions that can be tackled using large databases. SISAL provides instructions and examples of the various querying software to facilitate this sort of broader framing, and it organized an introductory workshop (to be repeated at future conferences) focused on using the database [*Ait Brahim et al.*, 2020].

SISAL is not a data repository, so people cannot search for an individual record in a Google-like setting. But if researchers need to find all the records of a particular age or within a particular region, they can do so easily, with a single command line in MySQL, for example. This is not something that can be done with repositories like NCEI, where one would have to painstakingly download one record after another.

We believe that this format of providing a diverse range of incentives for data generators, while at the same time providing validation for metadata through ongoing projects as well as different options for scientists to get credit for their work, is the best way forward for research databases like SISAL and for science broadly. Top-down enforcement solely from funding bodies and publications can ensure open access to data, but the

Table 1. Examples of Metadata Fields in the SISAL Database

Data Field	Drop-Down List Options	Percentage of Records for Which This Information Is "Unknown" in SISALv2
Speleothem type	Stalagmite Stalactite Flowstone Composite Other Unknown	3.0
Mineralogy	Calcite Secondary Calcite Aragonite Vaterite Mixed Unknown	2.8
Drip type	Seepage flow Seasonal drip Fast flow Mixture Unknown Not applicable	80.9
$\delta^{18}O$ water equilibrium	Yes No Unknown	55.9
Dating thickness	Not a drop-down list; percentage of individual speleothem records with no information for this field	65.1



Samples are milled from a speleothem using a small drill. Credit: Nikita Kaushal

research community must build the infrastructure to make this effort effective.

Ensuring Continuity

Considering SISAL's productivity since it began (3 database versions, 14 peer-reviewed articles, and 7 outreach articles), it appears this approach to database construction and management has been very successful. On the basis of communication within the research community, we believe the database contains 75% of all speleothem records published as of late 2019.

However, the creation and curation of the database is supported by time-limited grants whose terms will soon end, meaning that the SISAL Working Group will no longer be available to encourage data submission, quality check data, or update the database. One way of ensuring future continuity of this database is to have data generators use the standardized format (i.e., the preset spreadsheets) established by SISAL to produce data sets that can be submitted to a peer-reviewed or community-curated repository that, in turn, designates digital object identifiers for data sets. This process fulfills publication requirements for open-access FAIR (findable, accessible, interoperable, and reusable) data, makes data sets accessible for database updates, and gives credit to data generators for any future use.

Ideally, a platform will be created where experts from the research community can be incentivized to invest time to further quality check the standardized data sets uploaded to repositories and then add them to the SISAL research database. In turn, platforms (e.g., Linked Paleo Data, Neotoma, NCEI) containing multiple data sets holding speleothem, sediment, ice core, and other climate data sets can continue facilitating discussions to ensure standardization across proxies and archives.

The SISAL database and associated materials are freely accessible online. Further updates of the database will hinge on researchers volunteering and taking the lead, but these efforts at least will not be limited by the lack of a database infrastructure or of an active global speleothem community. Research databases and a community-level mindset of making data accessible for future projects are an efficient approach to furthering our understanding of Earth's past and future climates.

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AN UNBROKEN RECORD OF CLIMATE DURING THE AGE OF DINOSAURS

A scientific drilling project in China has retrieved a continuous history of conditions from Earth's most recent "greenhouse" period that may offer insights about future climate scenarios.

By Chengshan Wang, Yuan Gao, Daniel E. Ibarra, Huaichun Wu, and Pujun Wang

IN THE CRETACEOUS PERIOD, 100 million years ago, give or take a few tens of millions, Earth was a very different place than it is today. Flowering plants and trees had only recently evolved to coexist with conifers, ferns, cycads, and other groups, while a diverse array of dinosaurs was the dominant form of megafauna on land. The global climate in which these plants and animals thrived was also very different: warmer, steamier, and virtually devoid of ice.

Today Earth is markedly cooler than it was in the Cretaceous, and ice sheets and glaciers still cover large portions of the poles. Yet we know conditions are changing. The planet is already about 1°C warmer than it was during preindustrial times because of anthropogenic emissions of greenhouse gases like carbon dioxide (CO_2), and many governments are working to limit further warming to no more than 2°C (or even 1.5°C) above preindustrial levels [*Intergovernmental Panel on Climate Change* (*IPCC*), 2018].

Meanwhile, Earth scientists are critically evaluating the possibility and consequences of scenarios in which radiative forcing (the surplus in the amount of solar energy Earth absorbs compared with what it radiates back into space) drives temperatures beyond those targets. What will happen, they ask, if atmospheric CO_2 levels (pCO_2)—about 280 parts per million by volume in the preindustrial era and more than 415 parts per million by volume now—reach 800–1,300 parts per million by volume and the atmosphere warms by as much as 5°C by 2100 [*IPCC*, 2018]? The ensuing climate change would raise sea levels and could produce drastic shifts in the hydrologic cycle that would exacerbate hazards like drought, floods, fire, and extreme temperatures—all of which could severely affect ecosystems and humans around the world.

In this effort to project future climate scenarios, it is invaluable to investigate times in the geologic past when pCO_2 levels and temperatures were higher than they are today because these are the best natural analogues that we have to provide reference points for the future [*Tierney et al.*, 2020]. One such time of interest is the Cretaceous (145.5 million to 66.0 million years ago), when atmospheric conditions created an intense "greenhouse" climate on the planet.

In 2006, workers on the SK project, an ambitious terrestrial paleoclimatic and paleoenvironmental research effort in China's Songliao Basin, began drilling through the basin's rocks to obtain the first complete record of the terrestrial Cretaceous climate (Figure 1). The project, named SK from the Chinese Pinyin of the phrase "Songliao Scientific Drilling," is being conducted under the framework of the International Continental Scientific Drilling Program (ICDP) [*Wang et al.*, 2013a, 2013b; *Gao et al.*, 2019]. Findings following the first two phases of drilling have already revealed valuable insights. With the final phase of drilling just completed, we anticipate that new research will lead to additional revelations about past—and potential future—climate conditions.

> **In this effort to project future climate scenarios, it is invaluable to investigate times in the geologic past when atmospheric carbon dioxide levels and temperatures were higher than they are today.**

A Gold Standard for Reading Cretaceous Climate

The Cretaceous period is an archetypal example of a greenhouse climate. Atmospheric carbon dioxide reached as high as about 2,000 parts per million by volume, average temperatures were roughly 5°C–10°C higher than they are today, and sea levels were 50–100 meters higher [*O'Brien et al.*, 2017; *Tierney et al.*, 2020]. These conditions resemble the most extreme scenario that the IPCC has predicted could occur by the end of this century, with pCO_2 levels greater than 1,200 parts per million by volume and global temperatures roughly 4°C higher [*IPCC*, 2018].

The Cretaceous represents the last gasp of dinosaurs' dominance in Earth's ecosystems; in addition, it was a time of rapid evolutionary turnover and proliferation of mammals, birds, and angiosperms (flowering plants). For decades, the scientific community has been thoroughly engaged in understanding Cretaceous climate, especially how events such as the Chicxulub asteroid impact and Deccan volcanism contributed to evolution and to the extinction of nonavian dinosaurs and other biomes [*Hull et al.*, 2020]. Despite this intense interest, we still lack long and continuous continental geological records of the Cretaceous.

In northeastern China, the Songliao Basin sprawls over roughly 260,000 square kilo-

karl muscat/Unsplash

Fig. 1. Core segments from the SK drilling project in the Songliao Basin are stored in this facility in Beijing. Credit: Yuan Gao

meters and, buried amid layers of mudstone, siltstone, and other sedimentary rocks, holds rich petroleum resources that support the Daqing Oil Field, one of the largest oil fields in China and the world [*Wang et al.*, 2013a, 2013b]. The Songliao Basin is also one of the largest continental sedimentary basins and, with a maximum depth of more than 10,000 meters, preserves a continuous and complete terrestrial record of the Cretaceous [*Wang et al.*, 2013a].

The Songliao Basin preserves a continuous and complete terrestrial record of the Cretaceous.

The SK project includes three main scientific objectives. The first is to assemble, from drill cores, a terrestrial "gold pillar" for the Cretaceous—a new high-resolution standard for correlating and dating Cretaceous terrestrial and marine strata and for identifying key stratigraphic boundaries. Such boundaries include those marking the Jurassic-Cretaceous and Cretaceous-Paleogene (K-Pg) transitions, as well as terrestrial responses to Cretaceous oceanic anoxic events (OAEs) when oxygen levels in the ocean dropped precipitously.

The second objective is to study Cretaceous terrestrial climate change and its links to biological evolution and extinction in East Asia, which will help us understand the responses of northern midlatitude climate to greenhouse-driven change. The third objective is to understand the mechanisms and processes behind the massive accumulation of organic matter in this large, long-lived lake basin, which will enhance our knowledge of the petroleum resource in the Daqing Oil Field.

Three Phases and Four Holes

The drilling portion of the SK project included three phases (Figure 2). The first phase, SK-1, was completed in 2006–2007 with two boreholes drilled near Daqing, Heilongjiang Province. This phase recovered 2,486 meters of core dating from the Late Cretaceous to early Paleogene, which includes the 66-million-year-old K-Pg boundary representing the last mass extinction and the demise of dinosaurs [*Wang et al.*, 2013a; *Gao et al.*, 2015, 2019].

The second phase, SK-2, was completed in 2014–2018 in Anda County, Suihua, Heilongjiang Province. SK-2 drilled to a depth of 7,018 meters, the deepest ever by an ICDP project at the time, and recovered 4,134 meters of core. This core stretches from Permian-Triassic basement rock (roughly 200 million to 300 million years old) to Early Cretaceous sediments [*Gao et al.*, 2019].

Drilling for the third phase, SK-3, took place in September 2020 to February 2021 in Nong'an County, Changchun, Jilin Province, and approximately 1,600 meters of terrestrial sediments from the middle Cretaceous were recovered. This period was the warmest interval during the past 150 million years and includes OAE2 about 94 million years ago. This event is considered one of the largest perturbations to Earth's carbon cycle, a time when organic material piled up on the seafloor because of decreased oxygen levels in the ocean.

In total, the three phases recovered about 8,200 meters of terrestrial sediments spanning the entire Cretaceous.

Deciphering the Story in the Strata

Research since 2006 investigating the SK-1 and SK-2 cores has resulted in many multidisciplinary scientific achievements. A precise chronostratigraphic framework—basically, a timeline of sedimentary layers—that pins down dates to within 100,000 years has been established for the SK-1 cores. A variety of methods were used to construct this timeline: radiometric dating (analyzing the decay rates of different radioactive isotopes), magnetostratigraphy (tracking ori-

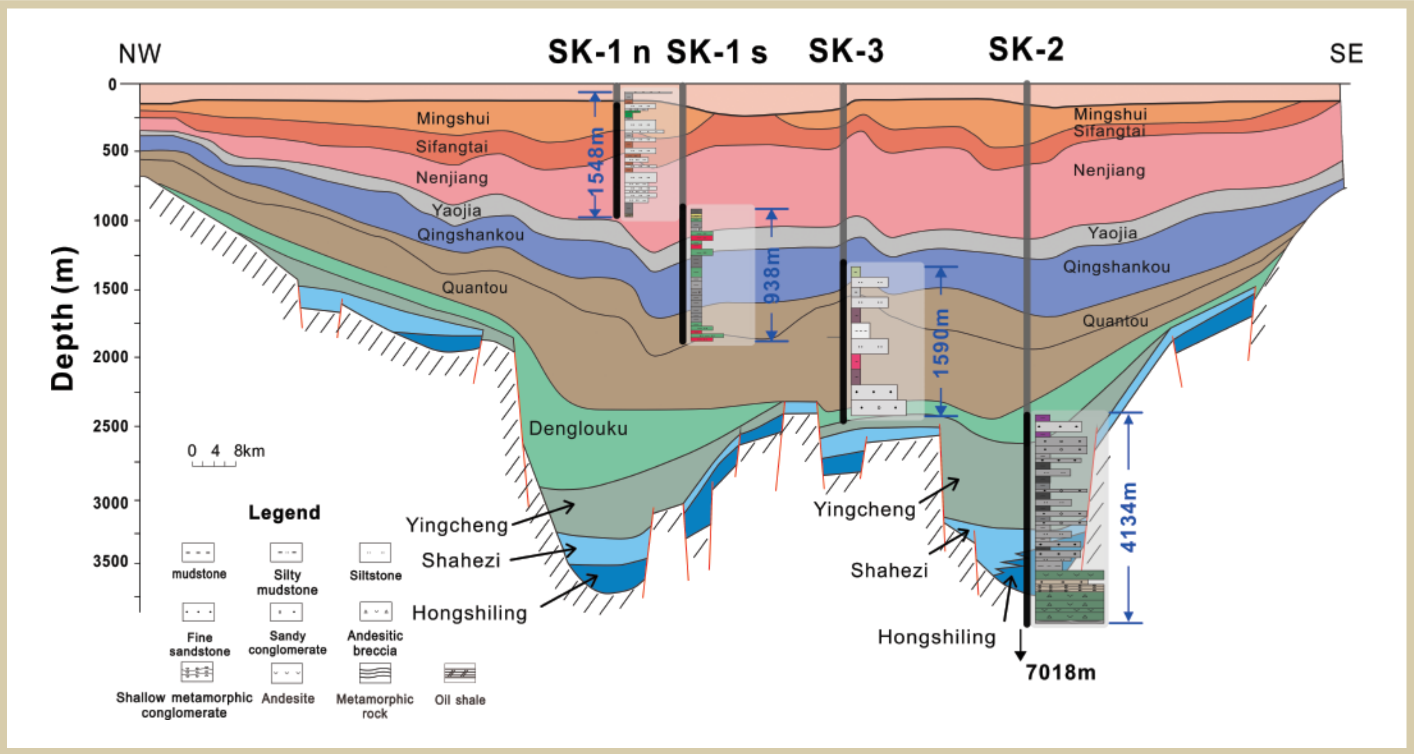

Fig. 2. Cross section of the Songliao Basin from northwest to southeast, showing named layers of sedimentary rock in the basin as well as the drilling and coring strategy of the three phases of the SK project.

entations of magnetic polarity preserved in rock layers), biostratigraphy (comparing fossils of particular ages across different layers), and cyclostratigraphy (tracking orbitally induced climate change cycles recorded in the sediments) [*Wu et al.*, 2014]. The resulting age model allows direct correlation of data from the Songliao Basin with data from sedimentary records collected elsewhere in the Cretaceous world.

Stable carbon and oxygen isotopes preserved in fossil ostracods, tiny lake-dwelling crustaceans, from the Songliao were found to record both an overall cooling trend through the Late Cretaceous and local signals of lake basin evolution [*Chamberlain et al.*, 2013]. Meanwhile, studies of sedimentary structures, mineralogical compositions, and stable isotopes in lake and paleosol (ancient soil) sediments revealed that large fluctuations in air temperatures over land, humidity, and moisture sources occurred during the last 10 million years before the dinosaurs went extinct [*Gao et al.*, 2015]. These findings have demonstrated that considerable climatic changes occurred before the demise of dinosaurs, and they have contributed to the ongoing debate over relationships between climate change, volcanism, the Chicxulub impact, and mass extinction [e.g., *Hull et al.*, 2020].

Findings based on studies of the SK cores have also fueled questions about ancient seawater incursions into the paleo-Songliao lake, evidence for which comes from microfossils of marine foraminifera and other marine organic biomarkers found in intervals of the SK cores [*Wang et al.*, 2013b; *Xi et al.*, 2016]. Although the cores dominantly record an ancient lake environment during this time, episodic and fast incursions of seawater may have altered the chemistry of lake water and promoted the preservation of organic matter under anoxic (oxygen-poor) conditions.

In total, the three phases of the SK project have recovered about 8,200 meters of terrestrial sediments spanning the entire Cretaceous.

Several widespread disturbances in Earth's carbon cycle—represented by OAEs—are known to have occurred during the Cretaceous from records of marine organic carbon burial. However, until recently, no direct links had been found between these marine data and records of terrestrial organic carbon burial during the same time. Analysis of the early SK cores revealed geochemical markers of OAE3 about 88 million years ago, the last Cretaceous OAE, that are contemporaneous with

The SK-3 drilling site in China's Songliao Basin has produced sediment cores to complete a record of terrestrial climate covering the Cretaceous period, Earth's most recent greenhouse climate. Credit: Yanwei Zheng

markers from the Western Interior Seaway (the shallow sea that covered much of what is now North America), providing evidence that this carbon cycle disruption indeed affected both land and sea [*Jones et al.*, 2018].

New Research on the Horizon

Research on the new core section retrieved during the recently completed SK-3 drilling phase will explore questions about the evolution of terrestrial climate in East Asia during the middle Cretaceous [*O'Brien et al.*, 2017; *Tierney et al.*, 2020]. These studies will help us understand just how hot the terrestrial realm was at that time and how hot it may get in the future in the northern midlatitudes, in which more than 40% of the global population lives today.

These studies will help us understand just how hot the terrestrial realm was during the warmest period in the past 150 million years and how hot it may get in the future in the northern midlatitudes.

This drilling will also provide a new, terrestrial record of OAE2, which is characterized by widespread distribution of marine black shales in major ocean basins and represents a major disturbance of the global carbon cycle. This Cretaceous terrestrial record from the SK cores in the Songliao Basin will be further integrated with counterpart marine records from the Western Interior Seaway in North America to understand more fully land-ocean linkages at Earth's surface, for example, whether lakes were anoxic, like the oceans [*Wang et al.*, 2013b].

The SK project team invites the geoscience community to participate in collaborative research investigating the SK cores, which span continuously from the Late Jurassic to the early Paleogene. Following regulations established by oceanic scientific drilling programs, the SK cores are available in a long-term repository in Beijing and are completely open to Earth scientists from all over the world.

We anticipate that through the combined efforts of experts from a variety of research fields, the more than 8,000 meters of cores from the Songliao Basin will elucidate the history and mechanisms of interactions among the climate system, biosphere, and lithosphere in the age of dinosaurs during Earth's most intense greenhouse state of the past 150 million years.

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Tracing Water from River to Aquifer

The coarse gravel bed of the Emme River in Switzerland, pictured here, is a major control of how much and how fast river water enters the aquifer beneath it. A new study in the watershed evaluated how water on the surface mixes and moves underground. Credit: Andrea L. Popp

The Food and Agriculture Organization has referred to mountains as the "water towers of the world." Globally, mountainous regions supply fresh water to billions of people through snowmelt and glaciers. Yet the 21st century is poised to strain these water resources. Climate models project changes to the timing and amount of precipitation, altered snow cover dynamics, and melting glaciers. These changes, in addition to other strains including increasing population pressure and contamination from past and present industry and agriculture, will affect the flow of rivers, water quality, and groundwater storage.

These pressures will require careful water management and possibly even redesigns of drinking water systems. In a new paper, *Popp et al.* describe a novel framework that uses dissolved noble gases to trace how river water mixes with groundwater and how quickly groundwater moves through an aquifer.

The case study took place in the Emme River catchment in the Swiss Alps, a snowmelt-fed system with a coarse gravel and sand riverbed overlying an aquifer. The authors used helium-4 isotopes to determine how river water and regional groundwater mix underground. They used radon-222 isotopes to infer travel times of recently infiltrated river water through the aquifer. The results helped the authors to estimate very young groundwater travel times, which is crucial for assessing water safety.

The study found that nearly 70% of groundwater in the watershed originates from recently infiltrated river water. The river water takes about 2 weeks to move through the aquifer, and the riverbed primarily governs infiltration. The high fraction of infiltrated groundwater and its short travel time through the aquifer suggest that it is vulnerable to increasing contamination and drought.

The novel method provides results in near-real time and allows uncertainties to be quantified by using a statistical approach: a Bayesian mixing model. The case study in the Swiss Alps demonstrates the viability and added value of the proposed framework. The authors suggest that when applied to different watersheds, the approach can highlight risks and vulnerabilities facing mountain-fed water supplies and improve water security worldwide. (*Water Resources Research*, https://doi.org/10.1029/2020WR028362, 2021) **—Aaron Sidder,** *Science Writer*

Tracking Oxygen in the Sargasso Sea's 18 Degree Water

Off the eastern coast of the United States in the Sargasso Sea, the Gulf Stream and its associated ocean currents create a thick, homogeneous layer of water that remains about 18°C year-round. Since its discovery in the late 1950s, this so-called 18 Degree Water has served as a testing ground for numerous studies of nutrient, carbon, and oxygen concentrations; biology; ocean mixing; and physics. In particular, the interplay between oxygen and carbon cycles in this layer of water has captured the attention of oceanographers as they attempt to map the flux of chemicals and energy for the entire Earth system.

In a new study, *Billheimer et al.* use data from biogeochemical floats in the northern Sargasso Sea to look at a core concept: the rate of remineralization, which is the speed at which organic molecules that include carbon and oxygen are converted into inorganic forms. Remineralization governs the amount of nutrients available to photosynthetic algae and thus weighs heavily in the carbon cycle. Remineralization, which varies with depth and with the seasons, is measured by oxygen usage and is linked to the maximum amount of particulate organic carbon that is produced in the surface layer and sinks through the water each year. The consistency of 18 Degree Water offers a useful natural laboratory to investigate these dynamics, especially during summer and fall, when the water layer is isolated from the atmosphere.

The new research offers a comprehensive picture of oxygen structure and usage in the northern Sargasso Sea. Using oxygen changes measured by the floats, the authors calculated that the study area is a net producer of fixed carbon and is responsible for exporting 2.9 moles of carbon per square meter per year from the upper 150–250 meters of the water column.

In addition, researchers discovered that the rate of remineralization in May–August is twice as high as it is in August–November. Oxygen increases in a layer near the surface from spring through fall because of photosynthesis; a much warmer layer at the sea surface keeps oxygen from outgassing. Oxygen is used up quickly in the layer just below this warm layer, driving down oxygen levels. Beneath this layer, into the thick 18 Degree Water layer, the oxygen usage rate decays with depth. According to the authors, the oxygen rate of change by itself underestimates the net production and remineralization in the top 150 meters of the ocean because of vertical mixing between the net oxygen production and oxygen usage layers. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2020GB006824, 2021) **—David Shultz,** *Science Writer*

Satellite Captures Detaching Iceberg in Near-Real Time

In September 2019, nearly a year to the day after NASA launched its Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), iceberg D-28, nicknamed Molar berg, separated from Amery Ice Shelf in East Antarctica. The split was the first major calving event on the ice shelf since around 1964, and it released a 210-meter-thick, 315-billion-ton iceberg into the Southern Ocean. The NASA satellite, which provides a detailed look at Earth's surface from an altitude of 600 kilometers, captured the entire event. This was the only large calving event to occur in the first 2.5 years of the satellite's mission (the second, from Brunt Ice Shelf, occurred this past February).

Ice shelves surround the Greenland and Antarctic Ice Sheets and form where the ice sheets meet the ocean. The ice shelves expand as the ice sheets collect snowfall and dwindle as the sheets melt or calve. Most large ice shelves are in equilibrium and experience significant mass loss only through large calving events, which typically occur once every few decades. Because these normal events are infrequent, they attract attention.

In a new paper, *Walker et al.* describe the D-28 calving event as seen through the lens of ICESat-2. The satellite provided before, during, and after observations as a massive chunk of Antarctica's third-largest ice shelf detached and drifted into the sea. The occasion provided an unprecedented look at a calving ice shelf with data captured by a modern, high-resolution satellite.

An aerial view of Amery Ice Shelf in Antarctica taken in 2006 shows one of the rifts making up the "loose tooth" rift system. The ICESat-2 satellite offers detailed observations of the rifts on the ice shelf and captured a long-anticipated calving event in near-real time in 2019. Credit: James Behrens, Scripps Institution of Oceanography, CC BY-NC-SA 3.0 (bit.ly/ccbyncsa3-0)

ICESat-2 revealed subtle topographic signatures of active rifts on the ice shelf that were not visible in high-resolution images captured by other Earth-observing satellites, like Landsat 8 and WorldView-3. These signatures included uplifted flanking walls, expanding crevasses, and significant acceleration in one rift just 12 days prior to calving. The observations suggest that the iceberg had been tearing away from the ice shelf at its base, hidden from view, for several years preceding the split.

The ICESat-2 data extend an unbroken chain of satellite observations of the Amery Ice Shelf rift system that stretch back to 2002. The 18-year time series shows the progression of cracks and crevasses on the shelf for nearly 2 decades before the 2019 calving event.

D-28 is now floating offshore Antarctica's Enderby Land, nearly 1,000 kilometers west of its origin. Meanwhile, ICESat-2 will continue to monitor the progression of Amery Ice Shelf in its new state. Data from the satellite will offer insights into the newly exposed ice shelf and will continue to be particularly useful for tracking the dynamic ice sheets of Greenland and Antarctica for years to come. (*Geophysical Research Letters*, https://doi.org/10.1029/2020GL091200, 2021) **—Aaron Sidder,** *Science Writer*

A Better Way to Understand Drought

A telltale "bathtub ring" of exposed, unvegetated rock on the mountainsides surrounding Morris Reservoir, east of Los Angeles, indicates that the reservoir is not full. Credit: Amir AghaKouchak

Scientists have few categories at their disposal to describe droughts, which are more complex than mere shortages of precipitation or surface water. For example, some local shortages can be invisible, as when water is transferred into a dry area from a distant source. Other shortages are chronic, with communities continuously requiring more water than is available, even in wet years. Some water shortages occur when water quality becomes so degraded that even though plenty of water may be available, little of it is usable. With such variation in conditions, scientists need better language to conceptualize droughts.

To address this deficiency, *AghaKouchak et al.* propose the idea of anthropogenic drought, which accounts for both natural variation and human actions. For instance, droughts are affected by local decisions about water and land use as well as by such global conditions as greenhouse gas levels and climate change. The authors suggest that scientists think of drought as a process with contributing factors, effects, and feedbacks rather than as simply a final product.

Droughts have far-reaching and often unexpected effects, including damage to local ecosystems, social unrest, and economic loss. The new framework acknowledges that many of these consequences drive the risk of drought even higher. For example, during the 2012–2016 drought in California, less hydroelectric power was generated. Energy providers turned to fossil fuels to meet demand, releasing greenhouse gases into the atmosphere. These emissions can worsen climate change, which in turn can increase the risk of extreme meteorological drought. Climate change has also led to an increase in "hot droughts," or periods that are both hotter and drier than normal. In hot droughts, less water is available at the same time that demand for water is greater because of the heat, and so the cycle continues.

The researchers say that human activities and decisions as well as related feedbacks should be integrated into new models that include both water and energy balances to achieve reliable modeling of drought as a process. By understanding how droughts develop as processes, scientists will be able to more accurately predict droughts, they suggest, allowing decisionmakers to respond appropriately and sustainably. (*Reviews of Geophysics*, https://doi.org/10.1029/2019RG000683, 2021) **—Elizabeth Thompson,** *Science Writer*

Upward Lightning Takes Its Cue from Nearby Lightning Events

In the chaos of a thunderstorm, upward moving lightning occasionally springs from the tops of tall structures. Scientists don't fully understand how upward lightning is triggered; it is likely a combination of multiple environmental factors, such as the background electric field and the structure's height. In a new study, *Sunjerga et al.* investigate how ambient lightning events near tall structures may trigger upward lightning.

The team created a simplified model of different scenarios that have been observed to occur near a tower before upward lightning. The model was able to explain the mechanism that causes upward lightning to spark from a structure as a result of nearby lightning activity.

According to the simulations, both the relatively slow leader discharge (the precursor paths that lightning will follow) passing above the tower and the much faster return stroke (the bright flash we see as lightning) in the vicinity of the structure can enhance the ambient electric field enough to trigger upward lightning from towers as short as about 30 meters—about 10 stories.

The study confirms the existence of a causal relationship between nearby lightning and upward lightning from towers. Additional research into factors like the local geography, the frequency of each scenario, and the wind speed can help further explain this unusual phenomenon. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD034043, 2021) **—Elizabeth Thompson,** *Science Writer*

Extreme Rainfall Statistics May Shift as U.S. Climate Warms

As Earth warms, extreme rainfall events are intensifying, thanks in part to the fundamental thermodynamic properties of air. This intensification will likely affect ecosystems and flooding around the world. However, to prepare for it, communities need a clearer understanding of how the timing, duration, and intensity of rainfall extremes will change.

A new study by *Moustakis et al.* presents a comprehensive assessment of future changes in the statistics of rainfall extremes across the contiguous United States, confirming that extreme events are likely to intensify and their duration and seasonal timing will shift.

The analysis draws on hourly precipitation data from 3,119 rainfall stations, as well as from high-resolution climate model simulations capable of predicting hourly rainfall at a spatial scale of about 4 kilometers. These simulations operate under a scenario in which global greenhouse gas emissions remain high throughout the 21st century.

The results of the study suggest that rainfall extremes will occur more often; on average, what is now a 20-year rainfall event will become a 7-year event across much of the country. Extreme events will also become more intense, with the greatest intensification predicted to occur in the western United States, the Pacific Coast, and the East Coast.

The study also predicts that rainfall extremes will occur more evenly over the course of the year, with the biggest seasonal changes happening in the plains, the Northern Rockies, and the prairies. Meanwhile, the duration of extreme rainfall events is predicted to shorten, with the Pacific Coast experiencing the biggest decrease. These changes could affect the ability of vegetation and soils to absorb water, thus affecting flood risk.

Further observations and model improvements will be needed to refine these predictions, the authors say. Nonetheless, these takeaways from the study could help inform efforts to prepare for future rainfall extremes. (*Earth's Future*, https://doi.org/10.1029/2020EF001824, 2021) **—Sarah Stanley,** *Science Writer*

Improving Air Quality in China's Greater Bay Area

Policies aimed at reducing residential and agricultural emissions in southern China could improve air quality for people living in Hong Kong and throughout China's Greater Bay Area. Credit: Dominick Spracklen

More than 70 million people live in China's Greater Bay Area, a booming megalopolis that includes Hong Kong, Macau, and nine other major cities. Air pollution is a major public health concern in this region and across China. Although recent emissions reductions have lowered exposure to some pollutants, other emissions have increased, and health risks persist.

Now research by *Conibear et al.* suggests that policies aimed at reducing both residential solid fuel use and agricultural fertilizer emissions in rural areas outside the Greater Bay Area could improve air quality both inside the Greater Bay Area and across China.

To reach these findings, the authors performed a quantitative analysis of various air quality policy scenarios and their potential impact. The researchers combined a regional chemical transport model with an epidemiological model to simulate the scenarios and estimate resulting exposure rates and health effects.

In the simulations, replacing 50% of solid fuel such as wood with liquefied petroleum gas in homes outside the Greater Bay Area reduced people's exposure to fine particulate matter ($PM_{2.5}$) by 3% within the Greater Bay Area and by 15% across China. According to the scientists, this decrease would prevent 191,400 premature deaths per year.

Meanwhile, simulations of a 30% reduction in ammonia emissions from agricultural fertilizer use outside the Greater Bay Area resulted in a 3% reduction in $PM_{2.5}$ exposure inside the Greater Bay Area and a 4% reduction across China, which would prevent 56,500 premature deaths per year. Reducing residential solid fuel use emissions would reduce both $PM_{2.5}$ and ozone exposure, but alternative policies could increase ozone levels, the analysis showed.

Currently, no policies are in place to specifically target residential solid fuel use and agricultural emissions in southern China. The authors note that efforts to address this opportunity will require cooperation across the region, both inside and outside the Greater Bay Area. (*GeoHealth*, https://doi.org/10.1029/2020GH000341, 2021) **—Sarah Stanley,** *Science Writer*

Past Climate Change Affected Mountain Building in the Andes

Climate change can affect the tectonic processes that deform Earth's surface to build mountains. For instance, in actively deforming mountain ranges such as the North Patagonian Andes, erosion caused by increased rainfall or glaciers might alter the structure of the mountains to such an extent that internal stresses and strains shift and reconfigure, changing how the terrain is molded.

Although theoretical evidence supports the influence of climate-driven erosion on mountain building, real-world data are lacking. Now *García Morabito et al.* present new data that support the theorized feedback between climate and tectonic deformation in the North Patagonian Andes.

Previous research has extensively explored the region's climatic and geologic history. Still, the timing, duration, and spatial patterns of tectonic deformation have not previously been examined with enough precision to draw strong causal connections between climate change and mountain-building processes.

To fill this gap, the researchers conducted field observations in the North Patagonian Andes, with a focus on the foreland basin that lies just east of the mountains and holds signatures of their tectonic history. Key to the analysis was dating of basin rocks and structures according to uranium-lead ratios and beryllium isotope levels. This dating enabled the researchers to analyze deformation at the level of individual faults.

Combined with previously collected data, the new observations revealed a clearer picture of the region's past: A period of widespread deformation and uplift appears to have occurred from about 13 million to 7 million years ago. Then, deformation decreased in the foreland, coinciding with the onset of glaciation in the mountains.

In the past few million years, as glacial erosion intensified, structural reconfiguration occurred, with foreland deformation coming to a halt while fault activity within the mountains increased. These findings match theoretical predictions, supporting the impact of climate change on mountain-building processes. (*Tectonics*, https://doi.org/10.1029/2020TC006374, 2021) **—Sarah Stanley,** *Science Writer*

New research provides real-world support for a long-standing hypothesis that glacial erosion in the North Patagonian Andes has influenced the tectonic processes that build the mountains. Credit: McKay Savage, CC BY 2.0 (bit.ly/ccby2-0)

Tropical Lakes May Emit More Methane

Methane is not the most abundant greenhouse gas in our atmosphere, but it is among the most potent. Roughly a quarter of global methane emissions come from natural sources, and freshwater ecosystems are the largest sources of atmospheric methane. Most of the data on methane dynamics in aquatic ecosystems come from boreal and temperate environments. Less is known about the fate of methane in tropical lakes.

To fill that gap, *Mendoza-Pascual et al.* tracked methane storage and other physicochemical properties in three volcanic crater lakes in the Philippines—Yambo, Pandin, and Calibato—where the northeast and southwest monsoons drive the regional climate. The team examined the impact of both weather fluctuations and mixing on methane concentrations. The three lakes are located relatively close together on Luzon Island and thus experience similar weather conditions but differ in physical characteristics, including maximum depth and thermal stratification.

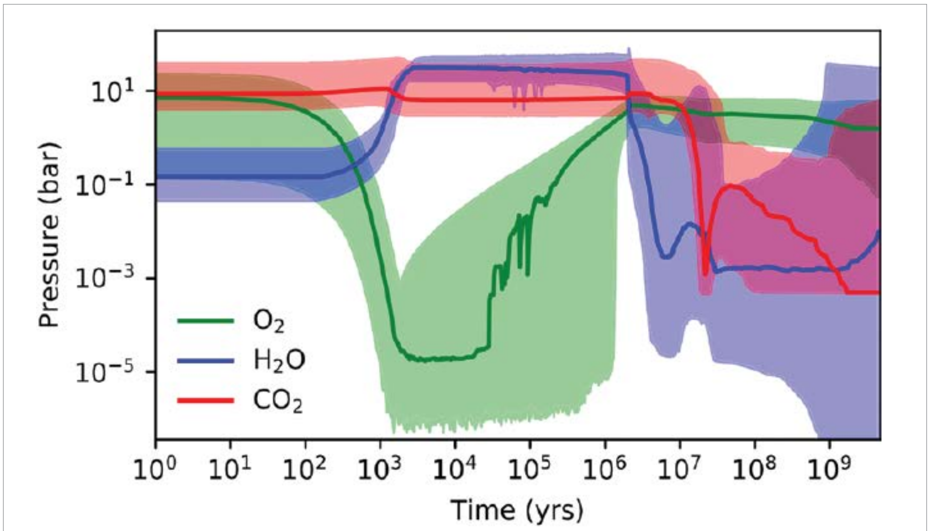
Data from tropical lakes in the Philippines, including Lake Yambo, pictured here, help scientists better understand methane dynamics in tropical systems. Credit: Barrera Marquez, CC BY 3.0 (bit.ly/ccby3-0)

The team collected water samples once a month between April 2018 and February 2019 at various depths in each lake and created vertical profiles of dissolved methane concentration, water temperature, and dissolved oxygen levels, using data from the Philippine Atmospheric, Geophysical and Astronomical Services Administration to track temperature, rainfall, wind speed, and air pressure over the same period.

The team found that mixing events, driven by changes in air temperature or pressure as the monsoon seasons progressed, affected methane storage in all three lakes. Strong stratification in the deeper lakes, the authors note, was more conducive to methane production and storage.

Water temperature was also linked to methane production, and higher concentrations of methane can be found in the profundal, or deep, zones of tropical lakes compared with temperate or subtropical lakes. Overall, the study suggests that lakes with higher water temperatures may contribute more methane emissions, with tropical lakes emitting between 58% and 400% more methane than lakes in more temperate zones. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2020JG005828, 2021) **—Kate Wheeling,** *Science Writer*

Is Atmospheric Oxygen a Planetary Signature for Life?



On "desert worlds" (planets with a low initial volatile inventory), a typical outcome of simulations of different amounts of volcanic outgassing, crustal weathering, and atmospheric escape is that atmospheric oxygen (O_2) is a dominant gas in the atmosphere for long periods in the planets' histories. The curves with shaded areas show results from a family of simulations that track changing pressures of three gases. Initial O_2 production from a steam atmosphere above a magma ocean, coupled with efficient escape and inefficient crustal weathering, leads to high O_2 levels. Credit: Krissansen-Totton et al., 2021

Oxygen came to compose a substantial part of Earth's atmosphere as a direct result of photosynthetic life, thus begging the question, Is oxygen a diagnostic signature for life on terrestrial planets around Sun-like stars? Only sometimes, according to *Krissansen-Totton et al.*, who model the long-term evolution of planets, including a magma ocean phase, volcanism, weathering, and atmospheric escape. Although they show that the most Earth-like worlds may generate significant oxygen only by biology, "water worlds" and "desert worlds" can have significant oxygen buildup even without life, because other geological processes that destroy oxygen are suppressed, whereas atmospheric escape generates oxygen over long periods of time. The work has implications for telescope design and the types of observations that would need to be made to distinguish biotic from abiotic oxygen on habitable exoplanets around Sun-like stars. (https://doi.org/10.1029/2020AV000294, 2021) **—Bethany Ehlmann**

Dry Soils Enhanced the 2018 Heat Wave in Northern Europe

Northern Europe is not a place we think of as experiencing water limitation. In this normally damp and cloudy region, increases in air temperature or sunlight are correlated with higher evapotranspiration rates and increased surface humidity. However, *Dirmeyer et al.* show that during the anomalously dry summer of 2018, soil moisture in Great Britain and large parts of Northern Europe dropped below a threshold at which increasing air temperatures no longer correlated with surface humidity. Instead, these regions switched to a water-limited regime, in which evapotranspiration could not cool the surface as efficiently. This further exacerbated extreme hot and dry conditions, a net positive feedback.

A companion Viewpoint article (https://doi.org/10.1029/2021AV000414) highlights the importance of identifying such thresholds in coupling energy and water balance between soils, plants, and the atmosphere and how improved models can help predict the course of increasingly common weather extremes in the future. (https://doi.org/10.1029/2020AV000283, 2021) **—Susan Trumbore**

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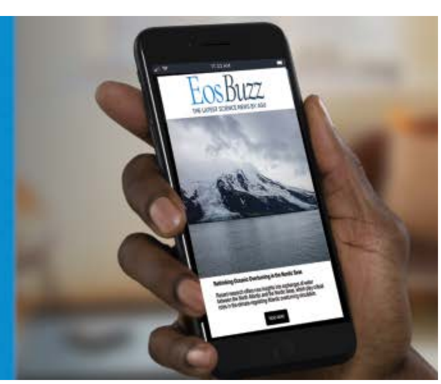
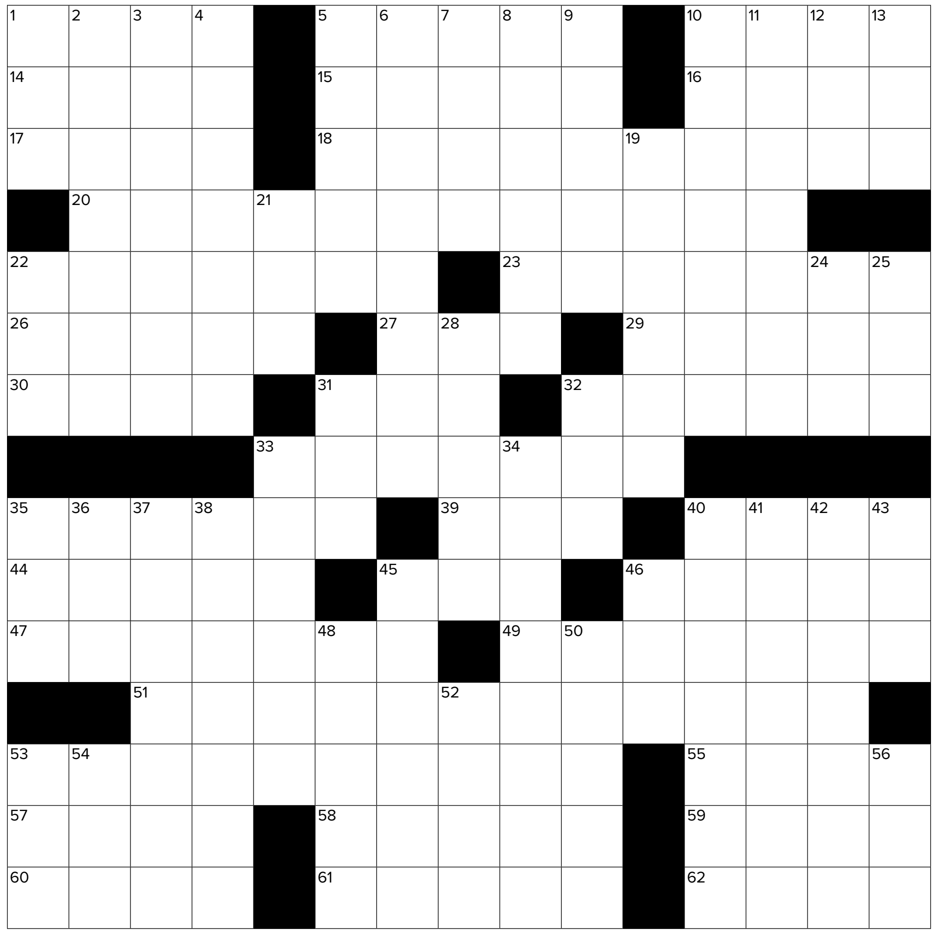


Not Just the Center

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Hawaiian tunas
5 Scope (or with the suffix -ious means "eager to succeed")
10 The edge of the Moon
14 *General Hospital* actress Sofer (or with an ending -me means to give a specimen a new designation)
15 Take care of
16 Taking care of business, as in "I'm ___ ___"
17 Rank above naval captain (abbr.)
18 Late 1800s pandemic
20 Related to geological accumulation, and with 33 and 51 across gives "___ ___ can be inferred from a ___ ___"
22 Either ORE: a cherry's pit or an ___ ___
23 Many deer have them
26 The search for life on Mars begins with ___
27 Material for tephrochronology
29 Happen again
30 Cowhide (without the vowels)
31 Ending for chor- or ration-
32 Red curry, pesto, and tahini
33 The past; see 20 across
35 Relating to a particular nature-based religion
39 Companion to downs
40 Measures of academic performance (abbr.)
44 Order of mites and ticks
45 Tarzan's mother?
46 First two syllables of the Gettysburg Address
47 Gobi, Nazca, and Antarctica
51 Type of collected earth specimen; see 20 across
53 What a volatile does in a vacuum
55 Archaic past tense of "know," as in "many puzzle-solvers ___ not that 3 or 4 consecutive circled theme letters were removed from each of the shaded entries"
57 Granular glacial snow
58 What erosion will do to the rock record
59 Prefix for middle-level cumulus
60 Where H fuses to He
62 Type, as of a movie or book
62 It can be pretty hot stuff
73 Everything else

DOWN

1 Pirate-y growl
2 Gesture of approval, as to a child
3 Drilling devices can give us an ___-___ look underground
4 It collects example specimens
5 Don't make ___ ___ of yourself
6 Written form of a song (see 55 across) OR *Wicked, Cats, Rent*
7 Someone from Great Britain
8 Prominent Hebrew prophet circa 700s BCE
9 Range in northwestern Wyoming
10 Places for events
11 Change the tone or pitch of voice
12 Unit of measure for landfill liner
13 Unit of energy (abbr.)
19 Shallow container holding newly received letters, job requests, or notes
21 Above, poetically
22 Cowhide hole puncher
24 Shakespeare's regret, "___ the day"
25 Players who put the ball through the hoop or over the goal line (see 55 across) OR students nearing graduation (abbr.)
28 You might do it to a tent or a chessboard
31 When added to "mount" yields a word that means the same thing
32 Units when buying shoes, gloves, or pants (abbr.)
33 Coiffure
34 Candor
35 Not "neatly folded"
36 Glacial boring that can reveal past climate
37 Manioc, rhyming with a word for liquid rock
38 Virginia, for example, or a Minecraft enemy
40 Final option in conflict resolution?
41 Juvenile, disparagingly
42 Stops
43 Sounds made by Kaa in "The Jungle Book"
45 Capital of Eritrea
46 U.S. federal agency for antitrust (abbr.)
48 ___ are to wheels as shoes are to feet
50 Where you might be to take a specimen of mid-ocean ridge basalt
52 Citation abbr.
53 Repeats at the end of performances
54 Type of healer
56 A person who is quite young

See p. 21 for the answer key.